Stability and performance of ground improvement using geocell mattresses under extreme weather

La stabilité et les performances de l'amélioration du sol en utilisant des matelas géocellules dans des conditions météorologiques extrêmes

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ABSTRACT: Owing to the rapid change in our living environment, extreme weather and its ensuing effect should become a focus of future engineering designs. Therefore, the underlying scope of this study is to evaluate the performance of a relatively new method in ground improvement under a harsh condition, simulating its response to intense rainfall as a result of extreme weather. The model tests show that the ground with the geocell reinforcement is of higher bearing capacity, compared to a natural ground without reinforcement. In addition, the tension cracks around the footing, which was observed in the natural ground, would not develop in the reinforced soil. The cause to the improved bearing capacity in the soil is in line with the finding through element testing suggesting that the geocell with soil infilled in the pocket as an integrated material equivalently becomes a cohesive material. On the other hand, the deformed geocell under the footing would develop a high passive earth pressure, larger than the water pressure possibly resulting in the tension cracks around the footing in a natural ground without the geocell reinforcement.

RÉSUMÉ: En raison de l'évolution rapide de notre cadre de vie, les conditions météorologiques extrêmes et leurs effets devraient devenir un foyer d'études techniques futures. Par conséquent, le champ d'application de base de cette étude est d'évaluer la performance d'une méthode relativement récente dans l'amélioration du sol dans des conditions difficiles, en simulant sa réponse à des précipitations intenses dues à des conditions météorologiques extrêmes. Les essais sur modèle indiquent que le sol renforcé à une capacité portante meilleure qu'un sol naturel non renforcé. En outre, les fissures de traction autour de la fondation ne se développent plus dans le massif renforcé par géocellules. La cause de l'amélioration de la capacité portante du sol est à relier à l'observation expérimentale que l'élément géocellule remblayé avec de la terre devient équivalent à un matériau cohésif. D'autre part, la géocellule déformée sous la semelle engendrerait une pression des terres passive élevée, plus grande que la pression de l'eau qui règenrait dans les fissures de traction développées autour de la semelle dans un sol naturel.

KEYWORDS: Geocell, ground improvement, extreme weather

1 INTRODUCTION

Geocell is a relatively new form of geosynthetics mainly used for geotechnical engineering. Different from the commonly used geogrid, geocell is considered a three-dimensional soil reinforcement material (Wang, 2007, Tafreshi and Dawson 2010). Its applications to engineering include soil retaining systems (Wesseloo et al., 2008, Ling et al. 2009, Leshchinsky et al. 2009,), ground improvements (Krishnaswamy et al. 2000, Dash et al. 2001, Leshchinsky and Ling 2012), and erosion control (Wu and Austin 1992). The results of element testing (Rajagopal et al. 1999) suggest that the geocell with soil infilled in the cell pocket as an integrated material equivalently becomes a cohesive material with its friction angle remaining more or less the same as the soil infill. Utilizing such a technique as for strengthening the soil, the dynamic performance of the soil retaining system with geocell wall facing was found satisfactory under the intense shaking of the Kobe earthquake, with full-scale shake table tests (Wang 2007, Ling et al. 2009, Leshchinsky et al. 2009). In addition to engineering aspects, geocell applications could reduce some construction expense partly due to easy and rapid installation of it, which can be constructed by low-skill crew without heavy machinery (Wang 2007, Ling et al. 2009).

Extreme weather and the ensuing effect, such as heavy rainfalls and floods, is the underlying cause to some recent catastrophes. For example, in 2009 the Shiaolin landslide in South Taiwan, destroying a local village completely and causing more than 400 casualties, was a result of an abnormal rainfall event brought by the Typhoon Morakot. The cumulative rainfall in three days reported at 1,700 mm is nearly equal to the annual rainfall of 1,800 mm around the region in the past few decades (Tsou et al. 2010).

However, owing to the continuing development of global civilization in need of keeping "exploiting" our living environment, global warming and extreme weather would not be expected to calm until we have a sound and effective response, say, the advent of new technology and the change of our living style and mind.

Therefore, this study aims to investigate the performance of the geocell-reinforced ground under a harsh environment (i.e., intense rainfall condition), which could be anticipated during its service life owing to the changing climate and extreme weather. This study is mainly assisted with laboratory works of geocell applications, and the details including experimental designs and setups, results and discussions are summarized and given in this paper.

2 EXPERIMENTAL DESIGNS, SETUPS AND MATERIALS

The experiment is to create a harsh condition for the ground to simulate its response to intense rainfall events as a result of extreme weather. Therefore, the water content in the soil model is added to a level around 20%, at which a thin layer of water can be observed on top of the model ground surface, simulating a situation that the ground is nearly immersed by water because of intense rainfall. The model tests were carried out with a sandbox fabricated in-house, which was deisgned at 1,670 mm in length, 550 mm in width, and 1,300 mm in height. In addition, the sandbox is perfectly sealed, preventing the water from draining out during testing. Therefore, a desired condition that the ground is excessively and rapidly saturated by heavy rainfall could be best simulated. In addition, for a better modeling of the unreinforced natural ground, the model was prepared at a loose to moderate condition with the unit weight around 19.6 kN/m^3, corresponding to a relative desntiy around 40% at 20% water content.

The sandy soil used in the model tests is the so-called China Standard ISO sand (Figure 1). The specific gravity of this soil is 2.65, with the maximum and minimum dry densities equal to 1.91 g/cm^3 and 1.62 g/cm^3, respectively. With our in-house triaxial tests, the angle of internal friction is around 38 degrees at a relative density of 70%.

Figure 2 shows the grain size distribution of this sand. It is worth noting that although the soil is also categorized into a SP (i.e., poorly graded sand) type of soil according to the Unified Soil Classification System, its size is not particularly uniform with some presence of small to large sand particles (see Figure 1), compared to the "popular" sand, such as the Toyuora sand or Nevada sand.

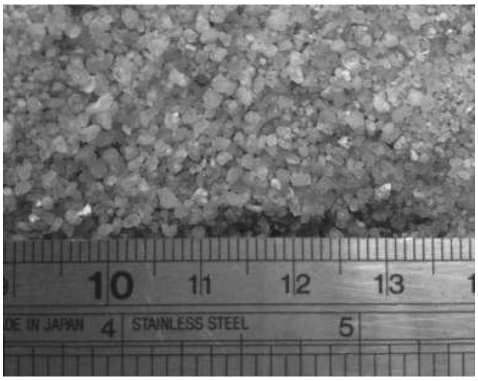

Figure 1. The China Standard ISO sand.

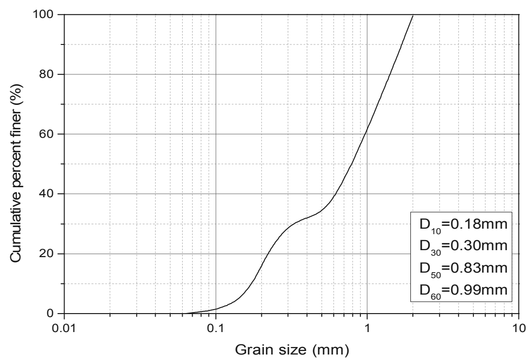

Figure 2. Grain size distribution of the China Standard ISO sand.

Figure 3 shows the appearance of geocell used in this study, which is manufactured by Beijing Orient Science & Technology Development Co., Ltd. (BOSTD) in China. The pocket size of the geocell is rather comparable to most commercial geocells in around 200 mm x 200 mm (Wang, 2007). Note that the geocell sample, courtesy of the manufacturer, is of no perforated holes on it. Also note that the 75-mm-high geocell sample is specifically adopted in this study, for a better fit to the dimension of the experimental layouts.

Figure 4 shows the installation of geocell during model preparation. The instrumentation includes LVDTs to measure the ground settlement and heave, and the particle image velocimetry (PIV) technique (White et al. 2003) to analyze the soil displacement in the ground subject to strip loading.

Figure 5 shows the schematic diagram of the experiment layout. With the footing's width in 100 mm, the ratio between the footing width to the geocell pocket size is around 0.5, close to the optimum ratio suggested in a related study (Dash et al. 2001b). Note that a layer of geotextile was installed between the geocell mattress and the foundation for preventing the wash-away of sand infills from the pocket. A total of three tests, two with geocell reinforcement and one without reinforcement, are reported in the following.

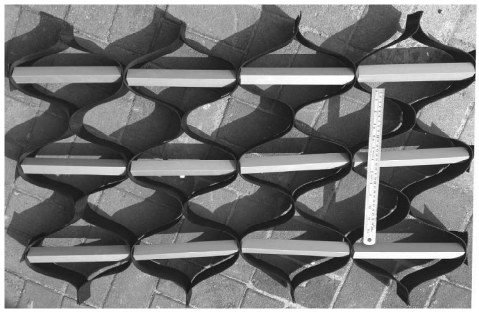

Figure 3. Top view of geocell mattress after expanding.

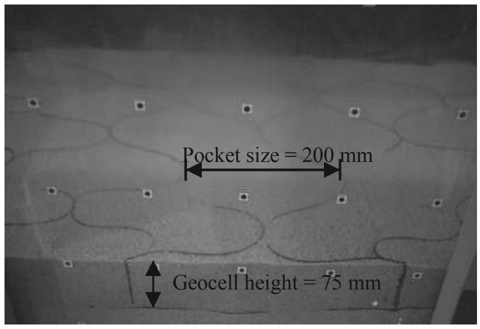

Figure 4. Installation of geocell in the soil model.

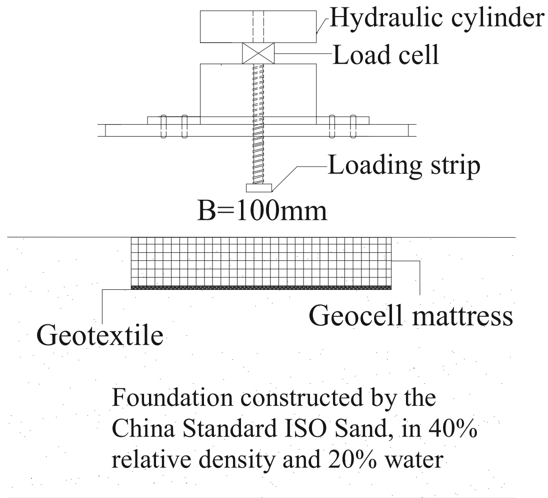

Figure 5. The schematic diagram of the experiment layout.

3 RESULTS AND DISCUSSIONS

3.1 *Bearing Capacity*

Figure 6 shows the relationships between load and settlement on the footing. At a given settlement, the ground with more layers of geocell is indeed of higher bearing capacity. Given 0.5 times of the footing width (i.e., 0.5B) being the tentative design settlement, the model tests show that the bearing capacities of the ground reinforced with one-layer and three-layer geocell mattresses are 1.4 and 2.2 times of the natural ground, without any reinforcement.

The increase of bearing capacity with the geocell reinforcement could be in line with the finding (Rajagopal et al. 1999) that the geocell filled with soil as an integrated material equivalently becomes a cohesive material, and in the meanwhile the angle of internal friction remains more or less the same as the sand infills. Therefore, in use of the Terzaghi's bearing capacity theory (see the textbook of Das 1999), the extra material cohesion adds the overall bearing capacity to the ground. More importantly, unlike the shear strength contributed by the frictional behavior becoming nominal as the effective normal stress is reduced significantly with the increase of pore pressure, the soil strength contributed by cohesion is independent of external stress and water pressure, or it should come to existence regardless of external stress condition.

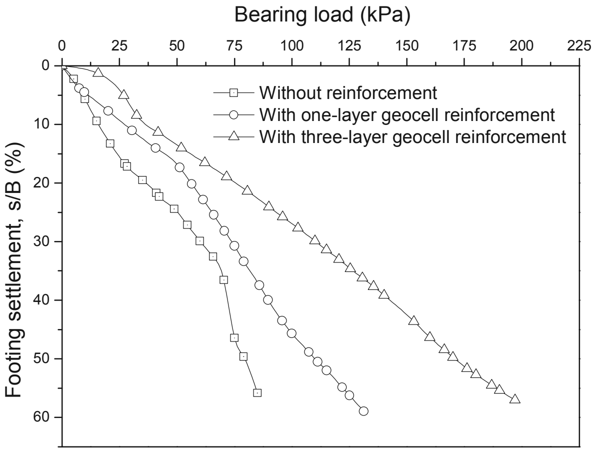

Figure 6. The relationships of load and settlement in the three model tests.

3.2 *Tension cracks*

Figures 7 and 8 show the model ground surface with and without the geocell reinforcement. For a "natural" ground without reinforcement, major tension cracks were observed very close to the footing. On the other hand, tension cracks in the two reinforcement tests were found located much further away from the footing, developing within the soil inside of the two ends of the geocell mattress.

The development of cracks close to the footing in the non-reinforcement test should be caused by the excessive pore water pressure excited in the soil due to external loading. As the lateral soil pressure less than water pressure, the tension crack should start developing. However, as the soil is reinforced by geocell, the deformed geocell under the footing tends to shrink the size of pockets, resulting in a large passive earth pressure that is larger than the water pressure, and therefore, the development of tension cracks is not allowed around the footing with the geocell reinforcement. This also possibly explains that the cracks would develop within the soil at the two ends of the geocell mattress, because the level of deformation in geocell is relatively small and the corresponding passive earth pressure is not large enough to compensate the excited pore pressure in the water-immersed ground.

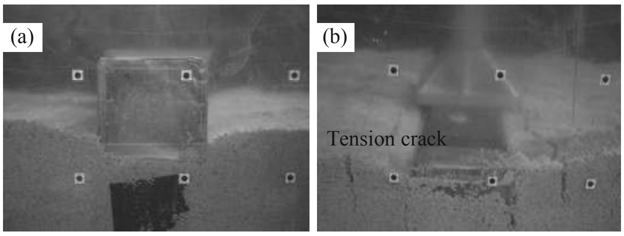

Figure 7. The side view of the model ground surface: (a) with geocell mattress; (b) without geocell mattress.

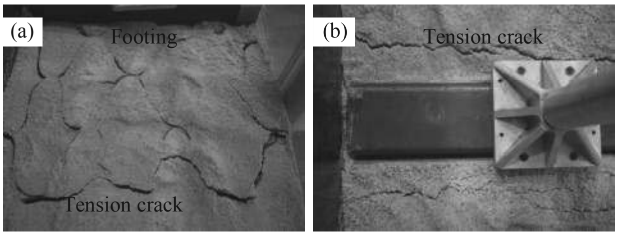

Figure 8. The top view of the model ground surface: (a) with geocell mattress; (b) without geocell mattress.

3.3 *Ground surface settlement and heave*

Figure 9 shows the ground surface settlement at different distances from the footing captured with LVDTs. In the three-layer geocell model, the ground surface tends to settle in a relatively large area, owing to the geocell-soil mattress acting as an integrated system. Simply speaking, the geocell-soil composites far away from the footing were pulled down owing to the geocell's structure, causing the ground settlement also observed relatively far from the footing.

On the other hand, for the natural ground without the geocell reinforcement, the soil adjacent to the footing was pushed upwards because of soil failure occurring right under the footing that would have formed a failure surface because of different levels of soil movement. It is worth noting that this mechanism and pattern in the ground deformation is well documented in a bearing capacity test (Das 2007).

The ground deformation captured with LVDTs is on the same page of the displacement field suggested by the PIV system, as shown in Figure 10. For the natural ground, the PIV displacement vector (Figure 10b) was pointing upwards near the ground surface, but at the same locations, the downward displacement vectors (Figures 10a) were observed as the ground was reinforced by geocell. It is worth noting that the displacement fields of the reinforced ground are relatively random compared to the natural ground, which should result from the fact that the surface processed by PIV is neither a completely reinforced soil nor a completely un-reinforced soil, as the boundary condition of the geocell structure shown in Figures 3 and 4.

4 CONCLUSIONS

This paper summarized the experimental work of using geocell in ground improvement under an intense rainfall condition, which recently recurs with an increasing rate owing to climate change and extreme weather. The result shows that the installation of geocell can indeed effectively improve the bearing capacity of the loose-to-moderate ground subject to high water content as a result of intense rainfall. The increased bearing capacity should possibly result from the "equivalent cohesion" as geocell and sand are integrated as a composite material. In addition, the deformed geocell inducing a large passive earth pressure in the soil within cell pockets would prevent the development of tension cracks close to the footing, which was observed in the natural ground without the geocell reinforcement.

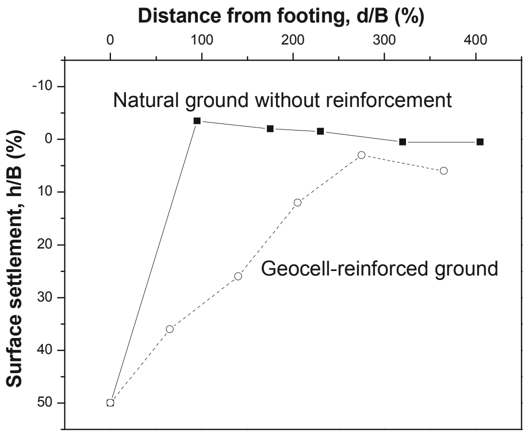

Figure 9. Ground surface settlement profile (negative values implying ground heave).

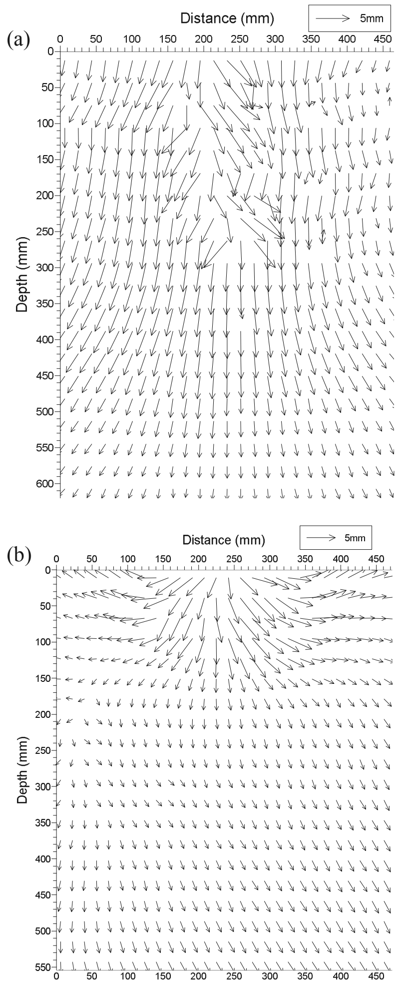

Figure 10. Soil deformation suggested with the PIV technique: (a) three-layer geocell-reinforced ground; (b) natural ground without reinforcement.

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