Effect of spacing of transverse members on pullout resistance of a square-shaped geocell embedded in sandy and gravelly backfill materials

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ABSTRACT

In order to investigate the influence of the compaction degree (Dc) of the backfill material and spacing of the transverse members (S) on the pullout resistance of a square-shaped geocell, a series of pullout tests were conducted on small scale models using square-shaped geocells with varying spacing between transverse members at a constant height. The geocells were embedded independently in a sandy backfill material and three gravelly backfill materials, varying the compaction degree (Dc) between 88% and 100%. All the tests were subjected to a 1 kPa surcharge. The results show that a higher compaction degree (Dc) yields a higher pullout capacity of the square-shaped geocell. It was also found that the overall pullout resistance of the square-shaped geocell is affected by the particle size of the backfill material, in which larger soil particles provide a larger pullout resistance. The findings also indicate that the spacing between transverse members becomes crucial when increasing the soil particle size, due to larger spacings can more efficiently accommodate larger soil particles and therefore mobilize its maximum pullout resistance. It is important to note that indefinitely increasing the spacing of the transverse members does not lead to an increment in the overall peak pullout resistance, since each material fully develops maximum pullout resistance at a given spacing, upper limit beyond which a larger spacing will not contribute to the development of larger pullout forces.

Key Words: geosynthetics, square-shaped geocell, pullout resistance, compaction degree, soil particle size

1 INTRODUCTION

Geosynthetic Reinforced Retaining Walls (GRS-RW) with full-height rigid (FHR) facing have been widely used in Japan for important infrastructure and major rehabilitation projects due to its high seismic stability, small deformability and cost effectiveness (Tatsuoka et al., 2007). Different types of geogrids and geotextiles have been conventionally used as planar tensile reinforcements of retaining walls, embankments and other soil structures. The pullout resistance of a geogrid soil reinforced element largely depends on the interlocking degree between the geogrid and backfill material (Palmeira 2008). However, in many cases, these conditions are not met due to local unavailability of the backfill material, potentially leading to a decrease in deformability and seismic resistance of the structure.

Ling et al. (2009) conducted a series of shaking table tests of a geocell-facing retaining wall, finding that geocells show higher seismic stability compared to the conventional geogrid-reinforced soil retaining walls, suggesting that three dimensional reinforcements can successfully be implemented to build gravity walls and soil reinforcement.

Considering the advantage of geocells to confine larger particles and a higher anchorage capacity when laterally pulled, Kiyota et al. (2009) and Kuroda et al. (2012) conducted a series of pullout tests using conventional geocells (diamond shape) to investigate the possibility of implementing geocell as a tensile soil reinforcement. The results suggested that despite the higher pullout force of the diamond-shaped geocell compared to several geogrids, its progressive deformation leads to a decrease in the overall stiffness. With this in mind, Han et al. (2012, 2013) conducted a series of pullout tests with a newly developed type of geocell, namely the square-shaped geocell. Comparing the pullout test results to those of the diamond-shaped geocell and several commonly used geogrids, it was found that the square-shaped geocell shows a higher pullout resistance as well as a higher pre-peak stiffness.

Moreover, Han (2014) and Mera (2015) investigated the influence of the existing relation between the height of the transverse members of the square-shaped geocell and particle size of the backfill material on the pullout resistance. The results showed that as the particle size of the backfill material is increased, an increase in the height of the transverse members yields higher pullout...
resistance due to an increment in the anchorage capacity of the geocell. However, they reported that there exists an upper limit at which a further increase in the particle size-height ratio does not yield a higher pullout resistance.

In order to acquire a deeper understanding of the factors affecting the overall pullout performance of the square-shaped geocell, it is important to conduct pullout tests under different testing conditions. This study, therefore, investigates the influence of the compaction degree ($D_c$) and spacing of the transverse members ($S$) on the pullout resistance of the square-shaped geocell. A series of pullout tests were conducted, which consist of three different types of square-shaped geocells with different spacing embedded in four different types of well compacted and low compacted backfill materials.

2 TEST APPARATUS

The pullout test apparatus shown in Fig. 1 was used in this study. The pullout tests were conducted under plain strain conditions, where the reinforcements were embedded in a backfill in the soil container. The pullout test apparatus consists of the soil container and a loading system. The dimensions of the soil container are 700 mm in length, 400 mm in width and 500 mm in height. The opening size on the front wall was kept constant at 45 mm.

The data logger used in this experiment was the portable data logger TDS-150, with 10 recording channels. The pullout test loading system was controlled by a motor, which provides a large range of pullout rates. In this study a constant pullout rate of 5 mm/min was applied. In order to measure the pullout forces of geocell, a 49 kN tensile load cell with accuracy of 98 N was attached to the pullout loading system. The geocell was firmly connected to a clamp, providing a perfectly rigid connection.

3 TEST PROCEDURE

Tables 1 and 2 show the details of the test cases. In order to achieve a well compacted backfill ($D_c>95\%$), manual compaction was done in 50 mm intervals, 10 layers in total. On the other hand, to achieve a low compacted backfill ($D_c<95\%$), the soil was poured at a minimum height until the desired height of the backfill was achieved. The geocell under consideration was placed in the soil container and then firmly fixed to the clamp. For preventing loss of soil from the opening at the front wall, clothes were used as a sealing arrangement. In order to measure the horizontal displacement of the geocell, linear LVDTs were firmly connected to the geocell using stainless inextensible wires at distances of 60 mm ($d_{60}$), 180 mm ($d_{180}$) and 360 mm ($d_{360}$) from the front wall. The wires were covered by stiff tubes in order to avoid contact between the wires and the surrounding soil. In addition, a vertical LVDT was installed on the top of the backfill at a distance of 60 mm ($V_{60}$) from the front wall in order to measure the vertical displacement of the backfill. Finally, a 1 kPa surcharge was applied on the top of the backfill by lead shot bags, letting the backfill to settle and dilate freely.

4 PULLOUT TEST MATERIALS

Silica sand No. 7 ($D_{50}=0.25$ mm), Gravel No.1 ($D_{50}=3.2$ mm), Gravel No.3 ($D_{50}=7.5$ mm) and Gravel No.5 ($D_{50}=14.2$ mm) were used as backfill materials. The square-shaped geocell was 360 mm in length × 350 mm in width. The height of the transverse and longitudinal members was kept constant at 25 mm and 45 mm respectively, while the spacing between adjacent transverse members was 60 mm, 120 mm and 180 mm for each type of geocell.
Table 1. Test cases for well compacted backfill.
(Transverse height = 25 mm, Longitudinal height = 45 mm)

| Test No. | Spacing (mm) | Backfill Material (mm) | Dₚ (%) |
|---------|--------------|------------------------|--------|
| SG1-S-C | 60           | Silica Sand (D₉₀=0.25) | 100    |
| SG1-G1-C | 60           | Gravel No.1 (D₉₀=3.2)  | 100    |
| SG1-G3-C | 60           | Gravel No.3 (D₉₀=7.5)  | 100    |
| SG2-G5-C | 120          | Gravel No.5 (D₉₀=14.2) | 97.7   |
| SG2-S-C  | 120          | Silica Sand (D₉₀=0.25) | 100    |
| SG2-G1-C | 120          | Gravel No.1 (D₉₀=3.2)  | 100    |
| SG2-G3-C | 120          | Gravel No.3 (D₉₀=7.5)  | 100    |
| SG2-G5-C | 120          | Gravel No.5 (D₉₀=14.2) | 96.6   |
| SG3-S-C  | 180          | Silica Sand (D₉₀=0.25) | 100    |
| SG3-G1-C | 180          | Gravel No.1 (D₉₀=3.2)  | 100    |
| SG3-G3-C | 180          | Gravel No.3 (D₉₀=7.5)  | 100    |
| SG3-G5-C | 180          | Gravel No.5 (D₉₀=14.2) | 98     |

Table 2. Test cases for poorly compacted backfill.
(Transverse height = 25 mm, Longitudinal height = 45 mm)

| Test No. | Spacing (mm) | Backfill Material (mm) | Dₚ (%) |
|---------|--------------|------------------------|--------|
| SG1-S-NC | 60           | Silica Sand (D₉₀=0.25) | 89     |
| SG1-G1-NC | 60           | Gravel No.1 (D₉₀=3.2)  | 95.6   |
| SG1-G3-NC | 60           | Gravel No.3 (D₉₀=7.5)  | 94.7   |
| SG2-G5-NC | 120          | Gravel No.5 (D₉₀=14.2) | 94.3   |
| SG2-S-NC  | 120          | Silica Sand (D₉₀=0.25) | 88.8   |
| SG2-G1-NC | 120          | Gravel No.1 (D₉₀=3.2)  | 91.4   |
| SG2-G3-NC | 120          | Gravel No.3 (D₉₀=7.5)  | 95.3   |
| SG2-G5-NC | 120          | Gravel No.5 (D₉₀=14.2) | 92.3   |
| SG3-S-NC  | 180          | Silica Sand (D₉₀=0.25) | 90.8   |
| SG3-G1-NC | 180          | Gravel No.1 (D₉₀=3.2)  | 93.6   |
| SG3-G3-NC | 180          | Gravel No.3 (D₉₀=7.5)  | 95.1   |
| SG3-G5-NC | 180          | Gravel No.5 (D₉₀=14.2) | 91.7   |

5 TEST RESULTS

Figs. 3a and 4a show the stress-strain behavior of the three implemented geocells embedded in the well compacted and poorly compacted backfill materials, respectively. The vertical displacement at the surface of the backfill materials is shown in Figs. 4b and 5b.

From Fig. 3a it can be noted that the geocells embedded in Gravel No.5 shows the highest pullout resistance, compared to those embedded in well compacted backfill materials with smaller particle sizes. Moreover, it seems that when the geocell embedded in well compacted Gravel No.1 and Gravel No.3, as the spacing of the transverse members (S) of the geocell increases, it yields a higher pullout resistance. However, this trend is not evident when embedded in Gravel No.5. Test SG2-G5-C shows a higher pullout resistance compared to that of SG3-G5-C, possibly because the peak value of SG2-G5-C has not yet been fully mobilized. For the cases of the geocells embedded in Silica Sand (SG1-S-C, SG2-S-C, SG3-S-C), all values show similar behavior, which might indicate that the spacing of the geocell has no influence in the maximum pullout resistance of the geocell.

Note that the three types of geocells embedded in well compacted Silica Sand (SG1-S-C, SG2-S-C and SG3-S-C) yields larger peak pullout resistances compared to those embedded in well compacted Gravel No.1 and Gravel No.3 backfills (SG1-G1-C, SG2-G1-C, SG3-G1-C, SG1-G3-C, SG2-G3-C, SG3-G3-C, SG2-G5-C, SG3-G5-C).

The increasing rates of the vertical displacement at the surface of the backfill for the well compacted backfills are shown in Fig. 4b. The well compacted gravelly materials show a higher increasing rate in the post-peak region, more notoriously as the particle size of the material increases. This behavior can be attributed to the development of thicker shear bands at the top and bottom interfaces of the geocell, to a larger extent in gravelly backfill materials.

Fig. 3. Well compacted backfill (a) Horizontal displacement (d₆₀) against pullout resistance, (b) Horizontal displacement (d₆₀) and vertical displacement (V₆₀).

Fig. 4a shows the pullout behavior of the geocell embedded in poorly compacted backfills. These results suggest that as the particle size of the backfill increases, the peak pullout resistance of the geocell also increases, to a certain extend contrary to the behavior observed in well compacted backfills. It can also be noted that the peak pullout values increases as the spacing (S) is extended. However it seems there is an upper limit up to which a further increase in spacing does not lead to larger peak pullout values. In this sense, as the spacing is increased beyond S=120 mm, the overall pullout resistance will rather be lower to both S-60 mm and...
S=120 mm. The different geocells embedded in a poorly compacted Silica Sand backfill (SG1-S-NC, SG2-S-NC and SG3-S-NC), show a similar behavior to that of the geocells embedded in a well compacted Silica Sand backfill. Namely, an increase in the spacing (S) has no influence on the overall pullout resistance of the geocell.

The increasing rate of the different geocells embedded in poorly compacted backfill is shown in Fig. 4b. It can be observed that gravelly backfills show a higher increasing rate than that of the Silica Sand backfill material, resulting therefore in higher pullout resistance. Furthermore, similar to the well compacted backfills, for poorly compacted gravelly backfills, an increase in the particle size and spacing leads to larger increasing rates of the vertical displacement.

**DISCUSSION**

The suggested pullout mechanism of the geocell is presented in Fig. 5. The pullout resistance of the geocell may be governed by the combined effect of the shear resistance of the backfill material along the geocell-backfill interfaces and the passive resistance developed within the geocells. The applied horizontal pullout force on the geocell results in shearing along the bottom and upper geocell-backfill interfaces, and therefore the shear strength of the soil will largely influence the pullout resistance. The applied horizontal pullout displacement also generates a passive resistance within the geocells along the transverse members. In this context, the height of the transverse members, the length of each unitary cell and shear strength of the backfill material are determinant factors of the pullout resistance.

Fig. 5. Schematic representation of pullout mechanism.

The influence of the compaction degree ($D_c$) on the pullout resistance and initial stiffness of the geocell is presented in Figs. 6a and 6b.

From Fig. 6a it is evident that an increase in the compaction degree ($D_c$) results in an overall increment in the peak pullout resistance of the geocell, regardless of the spacing of the geocell and backfill material. A higher degree of compaction could result in a higher shear strength of the soil and larger development of the passive resistance within the geocells. In this sense, the combined influence of the shear strength of the soil and passive resistance developed inside the geocells ultimately determine the maximum pullout capacity.

The initial stiffness ($E_3$) shown in Fig. 6b is defined as the secant modulus at $d_{so}=3$ mm, $E_3=\frac{T_{dso}}{3}$ (kN/m/mm). The initial stiffness of the geocells increase with an increase in the compaction degree of the backfill. The results indicate that a higher compaction degree also yields a larger initial stiffness ($E_3$) due to an increment in the density of the backfill.

The influence of the particle size ($D_{50}$) and spacing of the transverse members (S) on the peak pullout resistance embedded in well compacted sandy and gravelly backfill materials is shown in Fig. 7. The results show that in the cases of the Silica Sand and Gravel No.5 backfill materials, the effect of spacing is small. On the other hand, for the Gravel No.1 and Gravel No.3, as the spacing becomes larger, there is a clear increment in the peak pullout resistance. This behavior can be attributed to the extent of passive resistance development within the geocells. In the case of the Silica Sand backfill, the upper limit has been already reached and therefore extending the spacing does not lead to a higher passive resistance and ultimately a larger pullout resistance.
On the other hand, as the spacing of the geocell embedded in Gravel No.1 and Gravel No.3 increases, the pullout resistance becomes larger since the passive resistance can more extensively develop. Moreover, for the case of Gravel No.5 backfill, all three spacings yield similar pullout values. This suggests that larger soil particles need larger spacing in order to activate and mobilize its passive resistance. In this context, the used spacings for Gravel No.5 might be too short, and hence restrict the necessary deformation in the cell, which develops the pullout resistance. It is important to note that there is a potential for an increase in the peak pullout resistance for Gravel No.1, No.3 and No.5 when the spacing becomes larger.

Fig. 7b shows the influence of the particle size ($D_{50}$) and spacing of the transverse members (S) on the peak pullout resistance, embedded in poorly sandy and gravelly backfill materials. The ultimate peak pullout resistance of the geocell embedded in a low compacted backfill material yields lower pullout resistance, due to the decrease in the shear strength and dry density, associated with a lower compaction degree.

It can be observed that for the Silica Sand backfill, extending the spacing of the geocell does not yield a larger peak pullout resistance. Similar to the well compacted Silica Sand backfill, the passive resistance within the geocell could have been fully mobilized, and so extending the spacing beyond S=60 mm does not affect the development of the passive resistance.

Contrary to the well compacted backfill results, as the particle size of the soil increases, the geocell progressively yields larger peak pullout resistance. This behavior is possibly attributed to the fact that the ultimate passive resistance developed in the Silica Sand backfill is smaller to that of the not-yet fully mobilized passive resistance of the gravelly backfills.

From Fig. 7b it can also be observed that for the gravelly backfills increasing the spacing of the geocell beyond S=120 mm does not lead to an increment on its ultimate peak pullout resistance but rather develops lower peak pullout resistance. This behavior possibly indicates that increasing the spacing and particle size alone, without applying a compaction work, does not necessarily leads to larger peak pullout resistance.

7 CONCLUSIONS

The ultimate pullout resistance of a square-shaped geocell is governed by the combined influence of the compaction degree ($D_c$), spacing of transverse members (S) and particle size ($D_{50}$), along with those reported in previous literature (Mera 2015, Han et al. 2014, Kiyota et al. 2012, ). This study shows that a higher compaction degree ($D_c$) results in a higher peak pullout resistance. It is also important to note that the degree of compaction ($D_c$) also plays an important role in the initial stiffness of the soil and therefore the overall pullout resistance of the square-shaped geocell.
Moreover it is evident that the pullout resistance of the geocell is determined, along with the shear resistance at the backfill-geocell interfaces, by the extent of deformation developed within the geocells. This study also shows that the soil particle size (D50) also notoriously influences the ultimate pullout resistance due to its associated higher shear strength and passive resistance potential. Hence, the spacing of the geocell becomes very important, in which a larger spacing between transverse members more efficiently accommodate larger soil particles and allows larger deformations of the soil confined in the geocell.

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