Circular Footing on Geocell-Reinforced Granular Residue from Precious Gem Processing over a Sand Bed

J. Favretto, G.D. Miguel, M. Donato, M.F. Floss

Abstract. Geocell is a tridimensional confinement structure used for soil reinforcement, which significantly improves the performance of foundation systems. Aiming at a more sustainable engineering project and promoting a correct destination of a residual material, an alternative to fill the geocell is through the use of precious gem processing waste. The performance of geocell reinforcement filled with this granular residue overlying a sand subgrade, as well as the influence of geocell mattress height, have been studied by model tests in the laboratory. The layers were prepared in a test tank and subjected to static loading by a rigid circular footing. Footing load, footing settlement and displacements on the fill surface were measured during the tests. Comparing the tests on unreinforced and reinforced residue layer, the results indicate that the provision of geocell leads to a significant increase in the bearing capacity, presenting improvement factors of bearing capacity of up to 1.7. In addition, the reinforcement provides more uniform settlements and less expressive soil heaves around the footing.

Keywords: bearing capacity, gemstone residue, geosynthetic reinforcement, plate load test.

1. Introduction

The expansion of urban and industrial centers in developing cities, as well as the growth of infrastructure works, has led an increasing demand for materials to produce aggregates, cements, concrete, asphalt, etc. The production of aggregates comes, for the most part, from the extraction of primary sources. Engineering projects must be designed to minimize resource depletion, energy consumption, degradation and environmental impact. Therefore, the use of residues to replace natural materials is an alternative way of achieving those objectives. Many of the waste generated in the processing of industrial inputs or by-products is potentially capable of performing similar functions to those of natural aggregates (Sarsby, 2013). The decision to use such materials is based on technical needs, economic factors and environmental benefits.

Several gems and jewelry companies are located in the South of Brazil, whose activities consist in the extraction and processing of gemstones. These processes are responsible for generating a large amount of granular residue, in the form of refuse, semi-finished or little-benefited pieces, that ends up being stored improperly in the corporate yards, which could cause environmental damage (Thomé *et al.*, 2010). Aiming at the reuse of a waste material, some researches were developed using residues of scrolling of precious gems as geocell filling material in soil reinforcement systems (Miguel *et al.*, 2016; Baruffi *et al.*, 2016). With

similar purpose of using residues, Kolathayar & Kumar (2019) performed model tests on geocell retaining walls filled with tire crumb mixed with sand and observed that the mixture performed well as infill material.

Geocells are one of the main developments from the geosynthetics industry used to enhance the performance of soils and are used specifically for stabilization and protection applications in geotechnical engineering, such as beneath road pavements and railways, at the base of earth embankments and foundations (Bathurst & Jarrett, 1988; Bush *et al.*, 1990; Dash *et al.*, 2008; Sireesh *et al.*, 2009; Zhang *et al.*, 2010). It consists of a three-dimensional honeycombing structure of interconnected cells, devised by Webster & Watkins (1977) and Webster & Alford (1978), which contains and confines the soil within its pockets. The reinforcing mechanism in the geocells is by confinement of soil within its pockets that completely arrests the lateral spreading of soil (Dash *et al.*, 2003). Studies carried out on soils reinforced with geocells, taking as an example those conducted by Mandal & Gupta (1994), Dash *et al.* (2001) and Dash (2010), suggest that the effect of soil confinement results in a stiffer reinforcement system, capable of improving performance and increase resistance of the foundation. The height of the geocell is an important parameter in the behavior of geocell reinforced structures. It is found that with increase in geocell height, the rigidity of geocell mattress enhances (Sireesh *et al.*, 2009; Rai, 2010). The en-

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hancement is because with increase in height, the soil remains confined within the cell and the entire mattress deflects as a composite mass (Dash *et al.*, 2001).

Different infill materials have been tested through laboratory model tests (Han *et al.*, 2010; Hegde & Sitharam, 2015; Tavakoli Mehrjardi *et al.*, 2019). In general, the filling of the geocell is provided by granular materials, such as sand or gravel, because they have better interface properties and high control in the cell filling process (Rajagopal *et al.*, 1999; Biswas & Krishna, 2017).

This paper presents an experimental study conducted to investigate the benefits of the use of geocell reinforcement and the influence of two different heights of the geocell mattress on the behavior of the foundation. Attempting to reduce the consumption of primary aggregates and to reuse a residual material, promoting its correct destination, precious gem processing waste was used as filling material in the investigation. Plate load tests under static loading were carried out on geocell-reinforced residue over a sand bed.

2. Experimental Setup

Plate load tests have been conducted in a medium scale loading apparatus at the University of Passo Fundo, Brazil. The foundation bed was prepared in a wood test tank having 900 mm length, 900 mm width and 700 mm height. The footing used was made of a rigid steel plate with 150 mm diameter (D) and 12 mm thickness. The footing was centered in the tank and was loaded with a hydraulic jack supported against the reaction frame. To avoid interference of the tank walls with the stress zone propagated from the loading surface, the minimum dimension requirement should be about 5 and 2.5 times the plate size in plane and depth, respectively (Tavakoli Mehrjardi *et al.*, 2019).

2.1. Materials

The soil underneath the geocell mattress used was characterized by Donato (2007), indicating a poorly graded sand according to the Unified Soil Classification System, with unit weight of solids $\gamma_s = 26.30 \text{ kN/m}^3$, mean grain size $D_{50} = 0.16 \text{ mm}$, coefficient of uniformity $C_u = 2.10$ and of curvature $C_c = 1.00$. The minimum and maximum void ratios presented by Miguel & Floss (2017) are $e_{min} = 0.702$ and $e_{max} = 0.913$, respectively.

A diamond pattern polypropylene geocell was used in this study. Each cell is 270 mm long and 270 mm wide. It was tested two heights (h) of geocell mattress, 50 mm and 200 mm. The wall surfaces of the geocells are smooth, without texture or openings. The producers catalog suggests a transverse joint resistance of 900 N and 3,700 N for each height, respectively, tested according to NBR ISO 10321 (ABNT, 2013b). In addition, it indicates a wide-width tensile strength of geotextile equal to 26 kN/m and strain greater than or equal to 50 % for both geocells according to NBR ISO 10319 (ABNT, 2013a).

The pocket size is the equivalent diameter of the cell opening, in this case equal to 270 mm. It is found that this parameter must be smaller than the footing area, in such a way that the footing can cover at least one full pocket opening (Rai, 2010). However, a 150-mm-diameter plate was used to conduct the tests because the proposal was to evaluate if there would be benefits in the use of the reinforcement even for smaller contact surfaces.

Granular residue, resulting from the processing of precious gems in gem and jewelry companies located in southern Brazil, was used to fill the geocells. The original material was sieved, obtaining the particles passing through and retained in the sieves #3/8 (9.50 mm) and #40 (0.42 mm), respectively. The residue can be classified as well-graded sand according to the Unified Soil Classification System, with unit weight of solids $\gamma_s = 25.94 \text{ kN/m}^3$, mean grain size $D_{50} = 3.20 \text{ mm}$, coefficient of uniformity and curvature $C_u = 6.15$ and $C_c = 1.25$. The minimum and maximum void ratios are $e_{min} = 0.40$ and $e_{max} = 0.68$, respectively. The grain size distribution of sand and residue is shown in Fig. 1.

2.2. Foundation bed preparation

For the preparation of the subgrade, the sand was mixed with a moisture content $w_s = 10 \%$ and compacted to target relative density $D_r = 50 \%$. The selection criterion for the relative density value was the fact that this work is part of geosynthetic research group of University of Passo Fundo. The molding of the test layers started by spreading the homogenized sand to a total thickness of 400 mm, molded and compacted manually in 100-mm-thick layers. The uniform density of soil in the foundation bed was checked by placing small aluminum cylinders with known volumes at different locations in the test tank.

Figure 1 - Grain size distribution of materials.

In total, four tests were conducted, two unreinforced (Test Series A) and two reinforced (Test Series B). The reinforcement element overlying a 400-mm-thick sand bed was composed by a 50 or 200-mm-high geocell, filled with granular residue. The residue samples were molded dry ($w_r = 0\%$) and manually compacted in a single layer at relative density $D_r = 50\%$. In order to quantify the enhancement in bearing capacity due to the insertion of the geocell, unreinforced residue configurations were also tested, in the same heights. To avoid direct contact between the plate and the geocell, the reinforcement was placed to the full width of the tank at the depth of $0.13D$ below the bottom of the footing. Dash *et al.* (2001) reported good results of depth of placement of the geocell between 0 and $0.25D$ below the footing. The geometry of the test settings used in this investigation is shown in Fig. 2 and the test model details are provided in Table 1.

2.3. Testing procedure

The footing was placed at the top of the bed, centralized. In addition, the plate was positioned so that the loading occurred at the center of a cell, which is the worst loading situation. The loads were applied in small increments, according to NBR 6489 (ABNT, 1984), in equal

steps, and measured through a pre-calibrated load cell placed between the hydraulic jack and the reaction frame (Donato, 2007). Each incremental increase was maintained constant until the footing settlement had stabilized.

Settlements of the footing were measured by two dial gauges (Dg_1 , Dg_2) placed in diagonal directions. The displacements on the fill surface, settlement and heave, were measured by dial gauges (Dg_3 , Dg_4 , Dg_5) placed at a distance (x) of $0.83D$, $1.50D$ and $2.17D$ to the right of the footing center line, respectively. The geometry of the setup is shown in Fig. 2. In the absence of a clear failure, loading was applied until a footing settlement of 25 mm was reached.

In all the tests, the pocket size of the geocell or the equivalent diameter (d), width of the geocell layer (b), and the depth of the placement of the geocell layer (u) were kept constant, that is, $d/D = 1.80$, $b/D = 6.00$, and $u/D = 0.13$. The variable parameters were the residue configuration, unreinforced and reinforced, and the residue layer height, which were tested with relation $h/D = 0.33$ and $h/D = 1.33$. The footing settlement (s) and the surface settlement and heave (δ) were normalized by footing diameter to express them in non-dimensional form as s/D (%) and δ/D (%). In all the plots, settlements are reported with the positive sign and heave with the negative sign.

3. Results and Discussion

3.1. Bearing pressure settlement curve

Figure 3 represents the bearing-settlement response of the different test settings. The reference test on the sand subgrade was carried out by Miguel & Floss (2017).

It is observed that the presence of residue layer over the base soil reduces the bearing capacity of the sand, even when the reinforcement is used. This result indicates that the sand subgrade has greater stiffness than the material proposed to fill the geocells. The explanation could be the difference in the friction angle of the materials that, even though not measured, has influence on rigidity of soil. As the material is obtained from the processing of the stones, its particles have a more rounded shape which, according to Pokharel *et al.* (2010), results in a relatively weak material. Although the use of the precious gem waste as geocell filling material did not show improvement in the foundation

Figure 2 - Geometry of the reinforced foundation bed.

Table 1 - Details of laboratory model tests.

Test series	Type of test	Details of test parameters
A	Unreinforced	Variable parameter: $h/D = 0.33, 1.33$ Constant parameter: $D_r = 50\%$, $w_s = 10\%$, $w_r = 0\%$
B	Reinforced (geocell)	Variable parameter: $h/D = 0.33, 1.33$ Constant parameter: $d/D = 1.80$, $b/D = 6.00$, $u/D = 0.13$, $D_r = 50\%$, $w_s = 10\%$, $w_r = 0\%$

Notes: $b = 900$ mm (geocell width); $d = 270$ mm (pocket size of the geocell); $D = 150$ mm (diameter of the footing); D_r = relative density; $h = 50$ or 200 mm (geocell height); $u = 20$ mm (placement depth of the geocell); w_r = moisture content of the residue; w_s = moisture content of the sand.

Figure 3 - Variation of bearing pressure with footing settlement.

performance, the environmental benefits could justify its use. Proposing the insertion of this residue in soil reinforcement, new tests can be carried out with a better graded particle size distribution and higher densities.

In addition, another parameter has influenced the results. It is found that the decrease in pocket size increases the bearing capacity due to the overall increase of mattress rigidity. Also, the confinement promoted by cells is larger as the pocket size decreases (Dash *et al.*, 2001). Dash *et al.* (2003) suggest a relation $d/D = 0.8$. In this study, this is not verified, since the cell has a mean opening of 270 mm and the footing has a diameter of 150 mm, resulting in $d/D = 1.8$. Thus, the insufficient performance of the studied foundation is also related to the influence of this ratio, because the cell involves the whole dimension of the footing.

However, comparing only the results of Test Series A and B (unreinforced and reinforced residue), it is noted a clear increase in the resistance using geocell reinforcement, for both heights tested. For the unreinforced and reinforced tests on 50-mm-high geocell ($h/D = 0.33$), the bearing capacity verified at the end of the tests was 311 kPa and 396 kPa, respectively. For unreinforced and reinforced tests on 200-mm-high geocell ($h/D = 1.33$), the bearing capacity verified at the end of the tests was 226 kPa and 379 kPa, respectively. The ultimate bearing capacity increased around 27 % and 68 % for $h/D = 0.33$ and $h/D = 1.33$, respectively.

It was shown that the unreinforced section with a smaller thickness had higher ultimate bearing capacity than that with a larger thickness. As the residue is a weaker material in comparison to the sand, the increase of the residue layer decreases the resistance of foundation due to greater displacements of the material. Also, the firm bottom in the

thinner section contributed to the enhance the bearing capacity (Pokharel *et al.*, 2010).

Dash *et al.* (2001) states that the increase of geocell height improves the overall performance of the geocell mattress. However, Fig. 3 shows a similar behavior of reinforced sections for both heights, reaching very close bearing pressure throughout the test, including the ultimate pressure, in the rupture moment. Considering the geocell models tested, this means that the increase in geocell height does not enhance the bearing capacity of the foundation studied. As previously mentioned, this can be explained by the low resistance of the filling material tested.

3.2. Improvement factor I_f

The increase in the bearing capacity due to the provision of the reinforcement can be quantified through a non-dimensional parameter called improvement factor (I_f), which is defined as the applied pressure at a given settlement for the tests with reinforcement divided by the pressure at the same settlement without geocell. The factor has as reference limit a value equal to one, so the results of factors above the unit mean that the use of geocell contributes to an increased resistance. Figure 4 represents the variation of the improvement factors with the footing settlement, by comparing the results of Test Series A and B. The unit value is indicated in the graph. The reference test performed on sand bed was not used in this analysis because, as seen in Fig. 3, the soil resistance reduces with the overlying fill material. Therefore, the focus is to evaluate the performance improvement due to the use of the geocell.

The I_f value increases with the evolution of the settlement. For the 200-mm-high geocell, this increasing behavior

Figure 4 - Variation of improvement factors of bearing capacity with footing settlement.

ior was observed from $s/D = 3\%$. The results obtained for the improvement factor indicate that the influence of the geocell is more significant for higher levels of settlement and that higher values of I_f are observed for the greater height of geocell, reaching values of up to 1.27 and 1.68 for the 50-mm-high and 200-mm-high geocell, respectively. The variation of the values of I_f for the different geocell heights is due to the variation of the bearing pressure of unreinforced tests, since both curves (for $h/D = 0.33$ and

$h/D = 1.33$) of reinforced tests present similar behavior, as seen in Fig. 3.

3.3. Surface displacement

Surface displacement characteristics of the geocell reinforced residue over a sand bed are discussed in this section. Figure 5 represents the variation of the surface settlement and heave with the footing settlement for the unreinforced (Figs. 5A and 5B) and reinforced section (Figs. 5C and 5D).

Figure 5 - Variation of surface settlement and heave with footing settlement (A) unreinforced $h/D = 0.33$, (B) unreinforced $h/D = 1.33$, (C) geocell $h/D = 0.33$, (D) geocell $h/D = 1.33$.

In the unreinforced tests, surface heaving has been observed. In general, the displacements show the increase of the surface heaving with the increase of the plate settlement. Also, it is observed that the surface displacements are higher closer to the footing.

Contrary to what occurs in unreinforced soils, where higher heave is observed on the surface, in reinforced soils this heave is less expressive. According to Dash *et al.* (2001), this behavior is due to the use of geocell, which leads to a more uniform surface settlement. Because of the effect of the stress distribution, or slab effect, the applied loading is distributed over a wider area, resulting in lower stress transmitted to the base soil. Hegde & Sitharam (2015) noted, for different filling materials, that since the foundation did not undergo any failure, surface heaving was not observed in the presence of geocells. They mention

that the possible reason for this could be that the failure surfaces might have been arrested within the geocell pockets.

To complement the results of surface displacements, Figure 6 presents the progression of the settlement and heave profiles for each increment of load, expressed by normalized settlement. This type of graph is important because besides observing the direction of the displacements, it is possible to verify the differential settlement and the rotation of the footing. At higher loads a small change in the density of the bed is enough to cause differential settlement. The tilting of the footing is a common phenomenon in small scale laboratory tests (Hegde & Sitharam, 2015).

Both in Test Series A and B, unreinforced and reinforced sections, greater displacements were observed in test with larger thickness of residue. This may be related to compaction problems in certain areas of the test tank, since

Figure 6 - Surface settlement and heave profiles (A) unreinforced $h/D = 0.33$, (B) unreinforced $h/D = 1.33$, (C) geocell $h/D = 0.33$, (D) geocell $h/D = 1.33$.

it is difficult to maintain the homogeneity of the material in relation to grain sizes. Besides, as previously mentioned, another reason may be the low resistance of the granular residue layer, that allows the material to move easily under load application.

4. Conclusions

This paper presents the laboratory model results of load tests on circular footing supported on geocell-reinforced residue underlying sand subgrade. The plate diameter was a significant limitation of the tests, considering that the pocket size of the cell involved the whole dimension of the footing. This influences the resistance mechanisms of the reinforcement because the higher strength of the geocell is not mobilized. Based on the findings from the present investigation, the following conclusions can be made on the foundation performance.

- (i) Provision of geocell in the overlying granular residue improves the bearing capacity and reduces the surface heaving of the foundation, considering tests using the residue with and without geocell.
- (ii) The use of the geocell results in more uniform settlements and less expressive heaves of the soil around the footing. Higher surface heaving was observed in soil without reinforcement. This behavior was verified for both geocell heights tested.
- (iii) The largest displacements, as well as the lower resistance of the foundation, were observed in the unreinforced tests with a greater thickness of residue. Because of the low stiffness of the residue layer, displacements occur under vertical stress. In the thinner residue layer, the firm base soil contributed to the increase of the bearing capacity.
- (iv) Similar bearing pressure settlement behavior was observed for both geocell heights tested, indicating that this parameter does not influence the resistance of the foundation studied.

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List of Symbols

- b : Width of the geocell layer
 C_c : Coefficient of curvature
 C_u : Coefficient of uniformity
 d : Pocket size of the geocells
 D : Diameter of the footing
 D_{50} : Mean grain size
 D_r : Relative density
 e_{max} : Maximum void ratio
 e_{min} : Minimum void ratio
 h : Geocell mattress height / residue layer height
 I_f : Improvement factor of bearing capacity
 s : Footing settlement
 u : Depth of the placement of the geocell layer
 w_r : Moisture content of the residue
 w_s : Moisture content of the sand
 x : Distance from the footing center line
 δ : Surface settlement and heave
 γ_s : Unit weight of solids