Stress-strain response of sand reinforced with a geocomposite

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ABSTRACT: The mechanical properties of soils and, thus, of soil structures can be improved by using geosynthetic reinforcements. This beneficial effect depends on several parameters. Herein the mechanical response of the soil-geosynthetic composite material was studied using triaxial tests and the influence of the following parameters on the stress-strain response of the soil was analysed: effect of the reinforcement, number of reinforcement layers, vertical spacing between reinforcement layers; influence of the specimens' dimensions. The soil was a well graded sand with silt (8% of fine particles); the geosynthetic was a reinforcement geocomposite consisting of continuous filament non-woven, reinforced by high tenacity polyester yarns material. The stress-strain response of the reinforced soil was compared to that of the unreinforced soil tested under the same conditions, using triaxial tests. The inclusions improved the stress-strain response of the composite material, due to the additional confinement provided by the reinforcements; the compressibility of the reinforcement and the lack of large openings influence the volumetric strains. Increasing the number of reinforcement layers from 1 to 3 resulted in an improved stress-strain response of the reinforced soil, particularly for large strains. For lower strains the reinforcements had no significant influence on the load-strain curves of the specimens. The height of soil between adjacent layers of reinforcement is key to the performance of the reinforced soil specimens. The small dimension of the specimens may lead to overestimating the benefit from the reinforcement, particularly for low confining stress.

Keywords: triaxial tests, granular soil, number of layers, vertical spacing, dimension of specimens

1 INTRODUCTION

The mechanical properties of soils and, thus, of soil structures can be enhanced by using geosynthetic reinforcements. This beneficial effect depends on several parameters, for example: reinforcement form and type; number of reinforcement layers; vertical spacing between reinforcement layers; soil type; soil water content; soil relative density. The research presented herein aims at contributing to increase the knowledge on soil reinforced with geosynthetics by reporting triaxial test results where the influence of some of these parameters was studied, namely the number and the vertical spacing between reinforcement layers. The influence of the dimensions of the specimens on the observed response was also analysed.

There are several studies in the literature where the response of reinforced soil with geosynthetics is analysed using triaxial tests for granular soil (Chen et al. 2014, Nair and Latha 2014, Nguyen et al. 2013). The inclusion of reinforcements has been reported to induce an increase of the soil confinement and, as a consequence, increase the strength parameters of the soil-geosynthetic composite material.

Recommendations on the test procedure for triaxial tests of reinforced soil, including the selection of parameters to be analysed and their range, the type of test, the dimension of the samples can be found in the literature (Chen et al. 2013, Hamidi and Hooresfand 2013, Nguyen et al. 2013, Fatahi and Khabbaz 2012, Noorzad and Mirmoradi 2010, Zhang et al. 2008, Latha and Murthy 2007, Markou and Droudakis 2006, Zhang et al. 2006, Unnikrishnan et al. 2002, Haeri et al. 2000, Rajagopal et al. 1999, Ingold 1983).

The results reported herein are part of a wider research programme that included performing triaxial tests using two different soils and two different reinforcements, analysing the influence of the test conditions (test velocity, specimen dimensions, confining stress), the soil relative density and water content, the reinforcement layout (number of reinforcement layers and their spacing) and type of reinforcement.

2 EXPERIMENTAL PROGRAMME

This paper reports triaxial tests of a sand reinforced with a reinforcement geocomposite. The influence of the number of reinforcement layers, the vertical spacing between reinforcement layers and the dimension of the specimens on the mechanical response of the soil-geosynthetic composite material were analysed. The soil and the geosynthetic used within the test programme were characterised using laboratory tests.

2.1 *Soil and geosynthetic*

The soil tested was a residual soil from granite and can be described as a poorly graded sand with silt (Figure 1). Table 1 summarises some soil properties: percentage of fine particles (<0.074 mm); 10% (D_{10}), average (D_{50}) and maximum (D_{max}) grain sizes; coefficient of uniformity and curvature (C_u and C_c); density of the particles (G_s); maximum (e_{max}) and minimum (e_{min}) void ratio; compaction characteristics of the soil (ASTM D1557-12, modified Proctor tests), maximum dry density (ρ_{dmax}) and optimum water content (w_{opt}). The soil was classified using USCS, Unified soil classification system (ASTM D2487–11), and AASHTO classification system (AASHTO M 145-91-UL) as SW-SM, well graded sand with silt, or A-2, respectively.

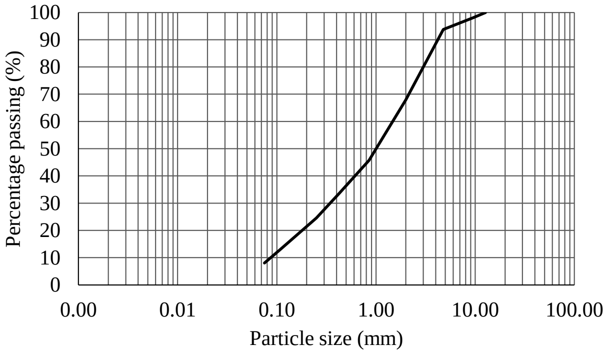


Figure 1. Particle size distribution of the soil tested.

Table 1. Properties of the soil tested.

%<0.074mm	D_{10}	D_{50}	D_{max}	C_u	C_c	G_s	e_{max}	e_{min}	ρ_{dmax}	w_{opt}
(%)	(mm)	(mm)	(mm)	(-)	(-)	(-)	(-)	(-)	(g/cm^3)	(%)
8	0.084	1.0	12.7	16.7	0.9	2.55	1.00	0.48	1.925	11.5

A reinforcement geocomposite (GC) consisting of continuous filament non-woven reinforced by high tenacity polyester yarns was used in the tests. Some characteristics of GC are summarised in Table 2: tensile strength, T_{max}; strain for maximum load, ε_{max}; force for 1% and 2% strain, $T_{1\%}$ and $T_{2\%}$; thickness for different normal pressures, 2kPa, t_{2kPa}, 20kPa, t_{20kPa}, and 200kPa, t_{200kPa}; mass per unit area, μ.

Table 2. Properties of the reinforcement studied, GC.

Direction	T_{max}	ε_{max}	$T_{1\%}$	$T_{2\%}$	t_{2kPa}	t_{20kPa}	t_{200kPa}	μ
	(kN/m)	(%)	(kN/m)	(kN/m)	(mm)	(mm)	(mm)	(g/m^2)
MD	54.6	10.6	7.5	12.5	2.14	1.59	1.07	325
CD	15.6	79.9	1.1	1.5				

2.2 *Triaxial tests*

The stress-strain response of soil and reinforced soil samples was assessed using unconsolidated undrained (UU) compression triaxial tests (ISO/TS 17892-8: 2004). The test conditions included: two sets of cylindrical specimens with different dimensions (diameter, D, and height, H) - D=70 mm, H=140 mm and

D=150mm, H=300mm; 83% relative density (dry density ρ=1.63 g/cm^3); 0.5 %/min axial strain rate. The results reported refer to dry specimens tested for confining stresses of 50, 100 and 150 kPa.

All specimens were prepared similarly; the reinforced soil specimens included layers of reinforcement (discs with 70 mm or 150mm diameter) placed at defined heights of the specimen (Figure 2) to study the influence of the number of reinforcement layers and of the vertical spacing between reinforcement layers. The specimens were assembled using layers of compacted soil (for example, specimens with H=140mm included 4 layers, 35 mm high each). The compaction was done manually by vibrating the soil and applying cyclic normal forces to each soil layer of the specimen. The vibration of the soil was done with a spatula and the normal force was applied with a cylindrical steel weight. The soil mass required for each specimen was quantified and the compaction of the soil layers was done in order to produce samples with the required relative density. To ensure the density of the specimens (unreinforced and reinforced) was comparable, the mass of soil used to prepare the reinforced soil specimens was adjusted, by removing the volume of soil to be taken by the reinforcements. The mass of soil was reduced in different quantities, depending on the number of reinforcement layers used in the specimens.

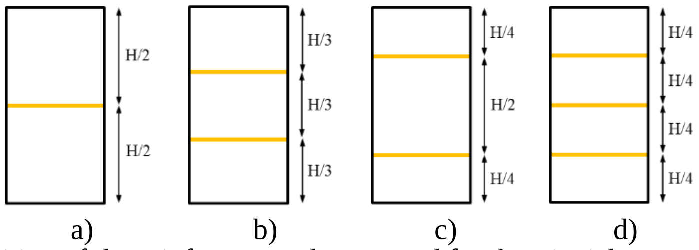


Figure 2. Number and position of the reinforcement layers used for the triaxial tests: a) 1 layer (H/2); b) 2 layers (H/3 and 2H/3), spaced H/3; c) 2 layers (H/4 and 3H/4), spaced H/2; d) 3 layers (H/4, H/2 and 3H/4), spaced H/4.

3 RESULTS AND DISCUSSION

Table 3 summarises the test results and includes: deviator stress, q; corresponding strain, ε; strength parameters, ϕ' and c'; secant stiffness modulus, E. Most of the tests on reinforced soil specimens had to be stopped before failure, when reaching the maximum strain permitted by the equipment; for those specimens no peak values are shown. Additionally, as the critical state was not always reached, values at the end of the tests are designated as final (subscript fin).

The following sections discuss the results in more detail, analysing the influence of the reinforcement, particularly the number of layers and of the spacing between layers, and of the dimensions of the specimens.

3.1 *Influence of the number and spacing between reinforcement layers*

The results show the influence of the reinforcement on the mechanical strength of the soil, as including reinforcement within the soil specimens increased the final deviator stress, q_{fin} (Table 3). Although many specimens did not reach failure before the tests were stopped, the final deviator stress of the reinforced specimens increased significantly relatively to the unreinforced ones: 38% (R_H140_1, σ_n=100kPa) to 395% (R_H140_3, σ_n=50kPa). For the specimens exhibiting a peak (such as R_H140_1), there was an increase of the maximum deviator stress (17% to 24%) and the corresponding strain (12% to 38%) relatively to the corresponding undamaged specimen (U_H140), for all values of the confining stress applied.

To better quantify the increase in strength observed, for each level of confining stress applied, the ratio between the deviator stress of a reinforced soil specimen to that of the corresponding unreinforced one was calculated. Figure 3 illustrates the strength ratio for the final stresses, SR_{fin}. All reinforced specimens exhibited a strength ratio SR_{fin} higher than 1, ranging between 1.38 and 4.95, for R_H140_1, σ_n=100kPa, and R_H140_3, σ_n=50kPa, respectively.

Figure 4 illustrates the deviator stress and volumetric strain versus strain for specimens H=140mm tested to a confining stress of 100kPa with different reinforcement layout. Increasing the number of reinforcement layers from 1 to 3 increased the performance of the reinforced soil samples, particularly for higher strains, as the final deviator stress increases significantly with the number of reinforcement layers. The inclusion of more reinforcement layers led to the reduction of the vertical spacing between adjacent reinforcement layers and an increased confinement of the specimens. Often, the contribution of the reinforcement to the shear strength of the reinforced soil composite material is interpreted as an additional confining stress (Sieira 2003; Ruiken and Ziegler 2008; Ruiken et al. 2010). When the spacing between adjacent reinforcement layers is small enough, the reinforcement can be interpreted as that additional confining stress acting along the full height of the specimen (Ruiken et al. 2010).

Table 3. Summary of the triaxial tests results.

Designation	H	Layers N.	Layers Position	σ_n	q_{max}	q_{fin}	ε_{qmax}	$\varepsilon_{q\ fin}$	ϕ'_{peak} (ϕ'_{fin})	c'_{peak} (c'_{fin})	$E_{\varepsilon=5\%}$
	(m)	(-)	(-)	(kPa)	(kPa)	(kPa)	(%)	(%)	(°)	(kPa)	(MPa)
U_H140	140	0	-	50	219.7	143.1	8.9	17.9	41.8 (37.7)	0 (0)	3.6
				100	434.3	344.3	9.7	17.8			7.28
				150	587	463.8	10.5	17.8			9.34
U_H300	300	0	-	50	-	231.9	-	17	- (38.2)	0 (0)	2.22
				100	-	402	-	17			3.74
				150	-	535.8	-	17			5.33
R_H140_1	140	1	H/2	50	271.9	246.3	10	17	43.4 (43.6)	9.7 (5.0)	4.15
				100	507.8	476.2	11.5	17			7.46
				150	705	695.8	14.5	17			9.52
R_H300_1	300	1	H/2	50	-	326.2	-	17	- (44.6)	- (2.1)	2.49
				100	-	587.7	-	17			3.97
				150	-	821.6	-	17			6.52
R_H140_2_1/3	140	2	H/3, 2H/3	50	-	558.8	-	17	- (45.0)*	- (68.4)*	5.03
				100	-	844.8	-	17			8.07
				150	-	1037.9	-	17			10.01
R_H140_2_1/2	140	2	H/4, 3H/4	50	-	330	-	17	- (41.9)*	- (29.7)*	4.52
				100	-	546.6	-	17			7.44
				150	-	732.5	-	17			9.56
R_H140_3	140	3	H/4, H/2, 3H/4	50	-	707.9	-	17	- (50.2)*	- (69.4)*	5.37
				100	-	1064.4	-	17			7.99
				150	-	1370.8	-	17			10.54
R_H300_3	300	3	H/4, H/2, 3H/4	50	-	492.2	-	17	- (40.6)*	- (64.6)*	2.84
				100	-	690	-	17			3.85
				150	-	868.6	-	17			6.12

* Specimens that did not reach failure

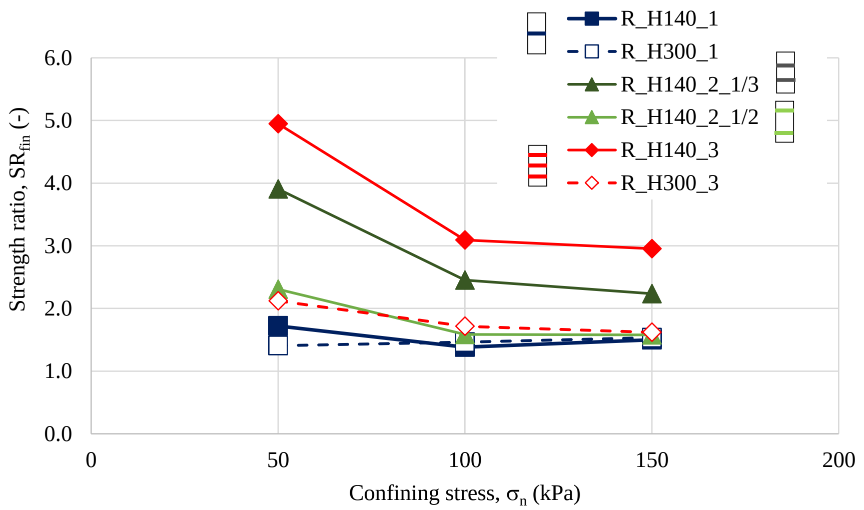
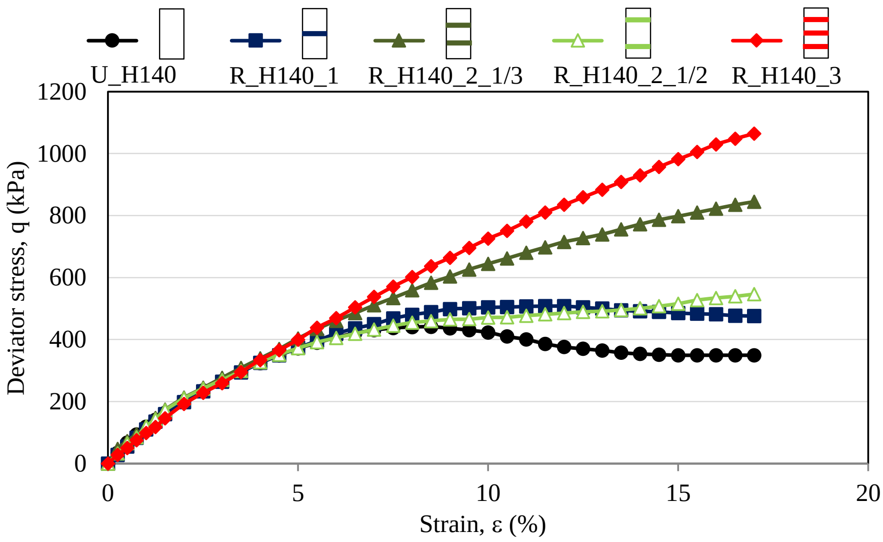


Figure 3. Strength ratio of the reinforced specimens: one layer of geosynthetic (R_H140_1 and R_H300_1), two layers of reinforcement with vertical spacing between the layers H/3 and H/2 (R_H140_2_1/3 and R_H140_2_1/2); three layers of reinforcement (R_H140_3 and R_H300_3) for specimens with H=140mm and H=300mm.



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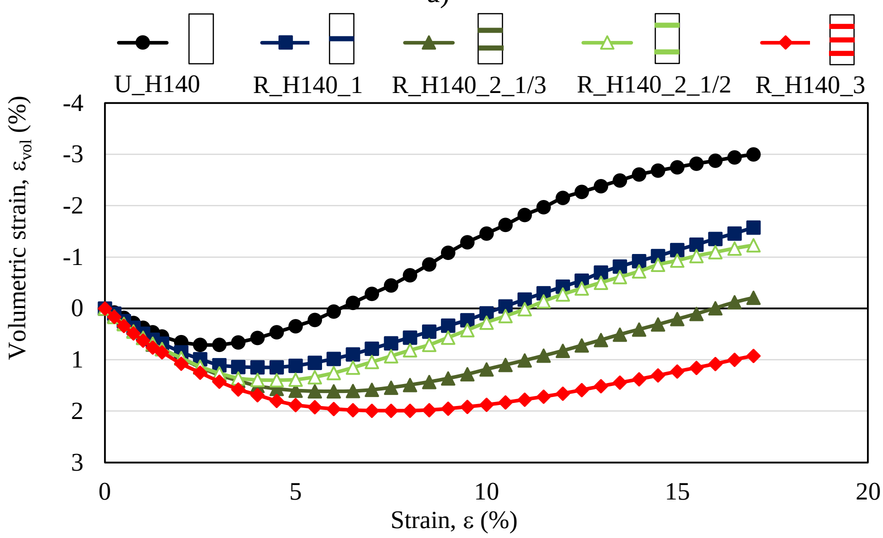


b)

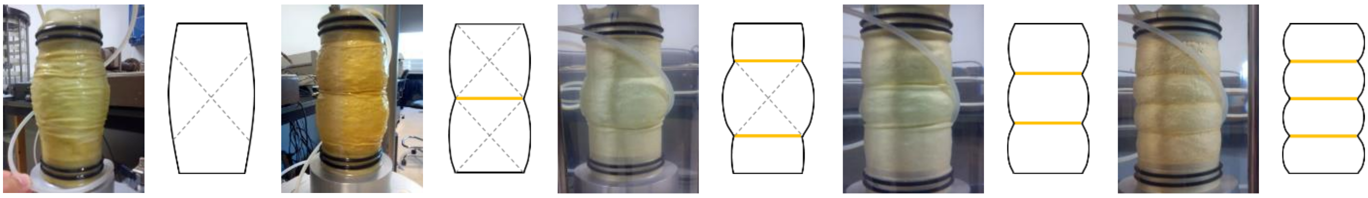
Figure 4. Triaxial tests results obtained for specimens of unreinforced (U) and reinforced soil with 1 layer (R_H140_1), 2 layers (R_H140_2_1/3 and R_H140_2_1/4) and 3 layers (R_H140_3) of reinforcement tested for a confining pressure of 100kPa: curves a) deviator stress and b) volumetric strain versus axial strain.

Figure 4 also illustrates how the reinforcement layers influence the volumetric strain of the specimens. All specimens exhibited an initial stage of contraction, followed by expansion. The reinforced specimens exhibited compressive volumetric strains higher than those of the unreinforced specimens tested under the same conditions; an increased number of reinforcement layers led to a higher contraction of the specimens. This is likely to be caused by the additional confinement provided by the reinforcement layers, mentioned above, combined with the compressibility of the geosynthetic layers. The latter becomes more important as the number of reinforcement layers within each specimen increases. For higher normal stress, the geosynthetic used as a reinforcement exhibits reduced thickness, as shown in Table 2. Additionally, as the reinforcement used in the tests has no large openings, it restricts the movement of particles above and below each layer of reinforcement, limiting the potential for dilation during expansion.

The reinforcement inclusions also influenced the stiffness modulus of the composite material. Two very different trends can be observed. On one hand, for lower strains ($\varepsilon<3\%$) there is no significant difference in stiffness (Figure 4), with the reinforced specimens exhibiting a slightly less stiff response than the unreinforced one. On the other hand, for higher strains the reinforced soil specimens exhibited higher secant stiffness than the corresponding unreinforced ones, as illustrated by the curves in Figure 4 and by the modulus of stiffness for 5% strain, $E_{\varepsilon=5\%}$ (Table 3). The results seem to indicate that a larger number of reinforcement layers results in increased modulus of stiffness for 5% strain. For smaller strains the reinforcements are being mobilised and this requires some deformations; for larger strains, the additional confinement provided by the reinforcement layers contributes to the increased stiffness of the specimens.

Comparing the response of reinforced specimens with that of the unreinforced soil, there is an increase of the strength parameters of the reinforced soil relatively to those of the soil (Table 3). It is important to point out that some of the values shown are low estimates of their true values, as many specimens did not fail. Figure 5 illustrates how the different reinforcement layout tested changed the deformation of the specimens and thus the failure mechanisms forming. While for the unreinforced specimens there was barrelling, the reinforced ones exhibited bulging between the top and the base of the specimen and the adjacent layers of reinforcement and between adjacent layers of reinforcement.

Saez (1997) distinguishes two mechanisms that can develop during triaxial tests of reinforced soil. On the one hand, tensile forces can be mobilised in the reinforcement, which benefit the composite material, however such effect is limited by the tensile strength of the reinforcement. On the other hand, relative displacements between the soil and the reinforcement can occur that enable mobilising shear strength in that interface; such effect is limited by the direct shear strength of the soil-reinforcement interface. In the tests reported herein, it was not possible to distinguish between the two mechanisms. Nevertheless, no tensile failure was observed when dismantling the specimens.



a) b) c) d) e)

Figure 5. Types of failure observed and typical failure surfaces observed in the triaxial tests: a) unreinforced soil (U_H140); reinforced soils with b) with one layer of geosynthetic (R_H140_1); c) and d) two layers of reinforcement (R_H140_2_1/3 and R_H140_2_1/2); e) three layers of reinforcement (R_H140_3).

The tests R_H140_2_1/3 and R_H140_2_1/2 included two layers of reinforcement in each specimen with different vertical spacing between those layers (H/3 and H/2, respectively), as illustrated in Figure 2b and 2c. The specimens with smaller spacing between the two layers of reinforcement (R_H140_2_1/3) exhibited a better response, with higher final deviator stress (for similar axial strain) and higher stiffness (Table 3). This indicates that, besides the number of reinforcement layers, the spacing between them is important.

Figure 4 shows that initially (for ε<3%) the response of the specimens with different vertical spacing between inclusions (R_H140_2_1/3 and R_H140_2_1/2) tested for σ_n=100kPa was very similar, both in terms of deviator stress and of volumetric strain. However, for higher axial strains the lower spacing between reinforcement layers resulted in higher deviator stress and in higher contraction of that specimen. As the layer of soil between the two adjacent reinforcement layers is shorter, the additional confinement induced by the reinforcements is higher, improving the stress-strain response and restricting dilation.

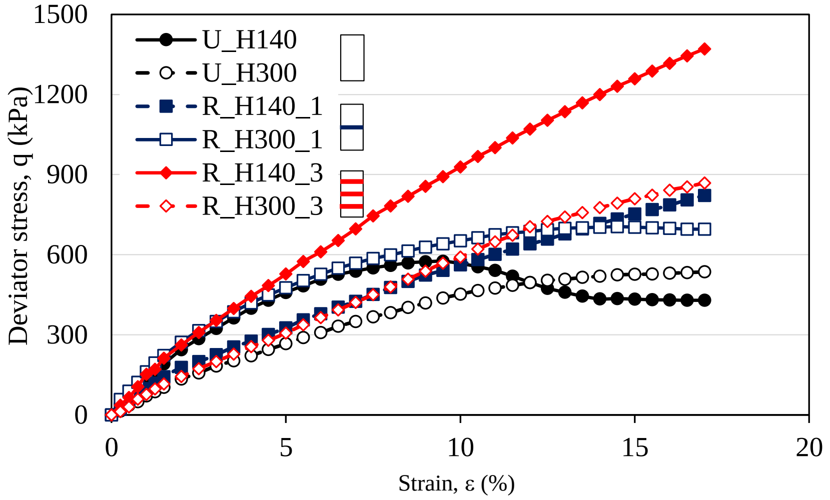
From Figure 4 it is also clear that the response of the specimens with 2 layers of reinforcement spaced H/2 is quite similar to that of specimens with one reinforcement layer. All those specimens have layers of soil of the same height (H/2, Figure 2b and 2c), which tend to deform in similar ways (Figure 4b and 4c). That similarity is more important for higher confining stresses, as illustrated in Figure 3.

The results indicate that besides the number of reinforcement layers, the vertical spacing between those layers is key to the stress-strain response of the reinforced soil specimens, as a reduction in spacing led to an increase of the strength of the specimens.

3.2 *Influence of the dimensions of the specimens*

To assess the influence of the dimension of the specimens on the results, data was obtained for specimens H=140mm, D=70mm and H=300mm, D=150mm (Table 3 and Figure 6). As many of the specimens did not reach a peak or failure, the results have to be analysed taking that into consideration. The smaller specimens, both unreinforced (U_H140) and reinforced with three layers of GC (R_H140_3), exhibited higher maximum deviator stress than the corresponding larger specimens (U_H300 and R_H300_3). That difference was more important for the specimens with 3 reinforcement layers. These results are in good agreement with the conclusions by Haeri et al. 2000 and Unnikrishnan et al. 2002. However, for the specimens reinforced with only one layer of reinforcement, the opposite trend was observed.

The specimens reinforced with one layer of GC exhibited a different trend. For the remaining specimens (unreinforced and with 3 layers of reinforcement), for similar deviator stress levels, the larger specimens (H=300mm) also had higher axial strains; the larger specimens tested exhibited larger compressive volumetric strains and a more pronounced contraction stage; the smaller specimens exhibited higher modules of stiffness. Increasing the size of the specimens from H=140mm to H=300mm led to a reduction of $E_{\varepsilon=5\%}$ of 42% for unreinforced specimens, 32% for specimens reinforced with one layer of GC and 42% for specimens reinforced with three layers of GC (σ_n=150kPa).



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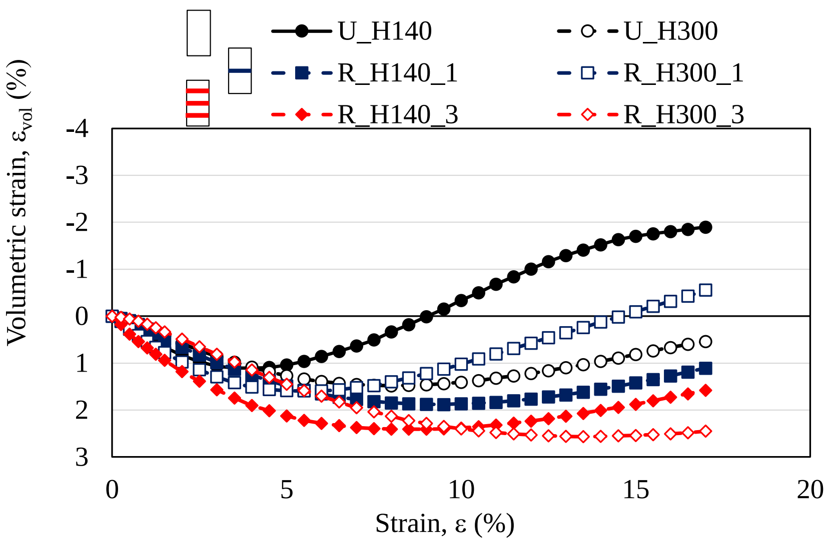

b)

Figure 6. a) Deviator stress and b) volumetric strain versus axial strain curves obtained for specimens with different dimensions (H=140mm and H=300mm) tested for a confining stress of 150kPa: unreinforced (U_H140 and U_H300) and reinforced soil with 1 layer (R_H140_1 and R_H300_1) and 3 layers (R_H140_3 and R_H300_3).

The specimens R_H140_1 and R_H300_3 showed a similar stress-strain response (Figure 6a). These specimens had layers of soil of 70mm and 75mm, respectively. Similarly, the specimens U_H140 and R_H300_1 had an analogous deviator stress – strain curve for lower strains (<6%); for higher strains the confinement due to the reinforcement led to an increased performance of R_H300_1. These results seem to confirm that the spacing between adjacent layers of reinforcement is key to the stress-strain response of the reinforced soil. The compressibility of the reinforcement and the restrained potential for dilation are likely to explain the differences observed for the volumetric strain of the pairs of specimens mentioned above.

4 CONCLUSIONS

In this paper, triaxial tests of sand reinforced with a geocomposite were reported, for different number of reinforcement layers and vertical spacing between those layers, as well as different dimensions of the specimens tested, and compared to the stress-strain response of similar unreinforced specimens. The main conclusions of this study can be summarised as:

- The inclusions improved the stress-strain response of the composite material, due to the additional confinement provided by the reinforcements; the compressibility of the reinforcement and the lack of large openings influence the volumetric strains.
- Increasing the number of reinforcement layers from 1 to 3 resulted in an improved stress-strain response of the reinforced soil, particularly for large strains. For lower strains the reinforcements had no significant influence on the load-strain curves of the specimens.

- The height of soil between adjacent layers of reinforcement is key to the performance of the reinforced soil specimens.
- The small dimension of the specimens may lead to overestimating the benefit from the reinforcement, particularly for low confining stress.

The dimensions of the specimens and the distances between reinforcement layers used in the tests are not realistic, therefore, the results need to be analysed taking those limitations into consideration.

REFERENCES

AASHTO. 1991. M 145. Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes.

ASTM. 2011. D2487. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System.

ASTM. 2012. D1557. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)).

ISO. 2004. TS 17892-8. Geotechnical investigation and testing - Laboratory testing of soil. Part 8: Unconsolidated undrained triaxial test.

Chen R.-H., Huang, Y.-W. & Huang, F.-C. 2013. Confinement effect of geocells on sand samples under triaxial compression. Geotextiles and Geomembranes Vol. 37, pp. 35-44

Chen, X., Zhang, J. & Li, Z. 2014. Shear behaviour of a geogrid-reinforced coarse-grained soil based on large-scale triaxial tests. Geotextiles and Geomembranes, Vol. 42(4), pp. 312-328.

Fatahi, B. & Khabbaz, H. 2012. Mechanical characteristics of soft clay treated with fibre and cement. Geosynthetics International, Vol. 19(3), pp. 252-262

Haeri, S.M., Noorzad, R. & Oskoorouchi, A.M. 2000. Effect of geotextile reinforcement on the mechanical behavior of sand. Geotextiles and Geomembranes, Vol. 18(6), pp. 385–402

Hamidi, A. & Hooresfand, M. 2013. Effect of fiber reinforcement on triaxial shear behavior of cement treated sand. Geotextiles and Geomembranes, Vol. 36, pp. 1-9.

Hong, Y.-S. & Wu, C.-S. 2013. The performance of a sand column internally reinforced with horizontal reinforcement layers. Geotextiles and Geomembranes, Vol. 41, pp. 36-49.

Ingold, T.S. 1983. Reinforced clay subject to undrained triaxial loading. Journal of Geotechnical Engineering, Vol. 109(5), pp. 738–744.

Latha, G.M. & Murthy, V.S. 2007. Effects of reinforcement form on the behaviour of geosynthetic reinforced sand. Geotextiles and Geomembranes, Vol. 25, pp. 23–32.

Markou, I. & Droudakis, A. 2006. Effect of triaxial compression testing factors on sand – geotextile interface friction. In: Kuwano J and Koseki J (eds) Proceedings of 8th International Conference on Geosynthetics, Yokohama, Japan, p. 1401-1404.

Nair, A. & Latha, G. 2014. Large Diameter Triaxial Tests on Geosynthetic-Reinforced Granular Subbases. Journal of Materials in Civil Engineering, Vol. 27(4), pp. 04014148 1-8.

Nguyen, M.D., Yang, K.H., Lee, S.H., Wu, C.S. & Tsai, M.H. 2013. Behavior of nonwoven-geotextile-reinforced sand and mobilization of reinforcement strain under triaxial compression. Geosynthetics International, Vol. 20(3), pp. 207-225.

Noorzad, R. & Mirmoradi, S.H. 2010. Laboratory evaluation of the behavior of a geotextile reinforced clay. Geotextiles and Geomembranes, Vol. 28, pp. 386–392.

Rajagopal, K., Krishnaswamy, N.R. & Madhavi Latha, G. 1999. Behavior of sand confined with single and multiple geocells. Geotextiles and Geomembranes, Vol. 17(3), pp. 171–184.

Ruiken, A. & Ziegler, M. 2008. Effect of reinforcement on the load bearing capacity of geosynthetic reinforced soil (paper 200). 4th European Geosynthetics Conference. Edinburgh, United Kingdom.

Ruiken, A., Ziegler, M., Vollmert, L. & Duzic, I. 2010. Recent findings about the confining effect of geogrids from large scale laboratory testing. 9th International Conference on Geosynthetics, (pp. 691-694). Guarujá, Brazil.

Saez, J. 1997. Caracterizacion geomecanica de geotextiles. Curso sobre técnicas generales de refuerzo del terreno y sus aplicaciones. Madrid, Espanha: Centro de estudios y experimentación de obras públicas (CEDEX) (*in Spanish*).

Sieira, A.C. 2003. Estudo experimental dos mecanismos de interação solo-geogrelha. Rio de Janeiro, Brazil: Tese de Doutoramento em Ciências de Engenharia Civil (Geotecnia), PUC-Rio (*in Portuguese*).

Unnikrishnan, N., Rajagopal, K. & Krishnaswamy, N.R. 2002. Behaviour of reinforced clay under monotonic and cyclic loading. Geotextiles and Geomembranes, Vol. 20, pp. 117–133.

Zhang, M.X., Javadi, A.A. & Min, X. 2006. Triaxial tests of sand reinforced with 3D inclusions. Geotextiles and Geomembranes, Vol. 24, pp. 201–209.

Zhang, M.X., Zhou, H., Javadi, A.A. & Wang, Z.W. 2008. Experimental and theoretical investigation of strength of soil reinforced with multi-layer horizontal–vertical orthogonal elements. Geotextiles and Geomembranes, Vol. 26, pp. 1–13.