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Cyclic and Post-cyclic Shear Behaviour of a Granite Residual Soil – Geogrid Interface

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Abstract

The dynamic frictional properties of the soil-geosynthetic interface play an important role in the design and stability analysis of geosynthetic-reinforced soil structures under repeated loadings, such as those induced by compaction, traffic and earthquakes. This paper describes a laboratory study carried out using a large-scale direct shear test device, aiming to investigate the cyclic and post-cyclic behaviour of an interface between a granite residual soil and a biaxial woven geogrid. In the cyclic direct shear tests, the interface was subjected to 40 cycles of sinusoidal displacement, with semi-amplitude and frequency ranging from 1-10 mm and 0.05-0.5 Hz, respectively. To evaluate the effect of the cyclic loading on the interface shear strength, monotonic direct shear tests were performed immediately following the cyclic tests. The results indicated that the loading frequency has little impact on the interface shear stiffness during the loading cycles. In contrast, the influence of the displacement semi-amplitude on the interface stiffness was found to be significant. The cyclic loading did not lead to the degradation of the post-cyclic interface shear strength. The post-cyclic peak shear strength tended to increase with the semi-amplitude of the shear displacement, which may be associated with an increase in soil density.

Keywords: Soil-geosynthetic interface, direct shear test, cyclic/post-cyclic shear behaviour, interface shear stiffness, semi-amplitude, frequency, granite residual soil

1 Introduction

The understanding of the soil-geosynthetic interface behaviour under cyclic loading conditions is essential for the design and stability analysis of geosynthetic-reinforced soil structures subjected to repeated loadings, such as those resulting from compaction, traffic and earthquakes. Over recent decades, many researchers have investigated static shear properties of soil-geosynthetic interfaces through direct shear tests (Bergado et al. 1993; Abu-Farsakh et al. 2007; Liu et al. 2009; Ferreira et al. 2012, 2013, 2015). In contrast, experimental data concerning the behaviour of such interfaces under cyclic loading conditions is very scarce (O'Rourke et al. 1990; Ling et al. 2008; Vieira et al. 2013).

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In the seismic design of geosynthetic-reinforced soil structures, it is common to use the interface shear strength evaluated under monotonic conditions to analyse the sliding stability along the interface between the geosynthetic and the reinforced fill or the foundation. The Federal Highway Administration (FHWA) suggests the use of the interface friction coefficient, determined from soil-geosynthetic direct shear tests in accordance with ASTM D 5321, in sliding stability analyses of geosynthetic-reinforced soil retaining walls under static or seismic conditions. However, there are few previous experimental studies showing that under dynamic loading no reduction occurs in the soil-geosynthetic interface shear strength.

In this study, the cyclic and post-cyclic shear behaviour of an interface between a granite residual soil and a biaxial woven geogrid was investigated through large-scale direct shear tests. The influence of soil density, displacement amplitude and loading frequency on the interface shear stiffness was evaluated and discussed. The effect of the cyclic loading on the interface shear strength was assessed by comparing the results from monotonic direct shear tests carried out immediately after the cyclic tests with those obtained from monotonic tests on fresh specimens.

2 Experimental Research

2.1 Direct Shear Test Device

The large-scale direct shear test device used in the present study (Figure 1) was developed during previous research at the University of Porto (Vieira et al. 2013). The device allows the analysis of the direct shear behaviour of soils, soil-geosynthetic and geosynthetic-geosynthetic interfaces under monotonic and cyclic loading conditions.

The apparatus is composed of a shear box, divided into upper and lower boxes, a support structure, five hydraulic actuators and respective fluid power unit, an electric cabinet and several internal and external transducers. The inner length, width and thickness of the upper and lower boxes are 600 mm × 300 mm × 150 mm and 800 mm × 340 mm × 100 mm, respectively. The upper box is fixed in the horizontal direction and vertically moveable through hydraulic actuators installed on its edges. The lower box is rigidly fixed to a mobile platform running on low-friction linear guides and its horizontal displacement is controlled by a hydraulic actuator. The normal stress is applied by a rigid plate with pressure-controlled double acting linear actuators and recorded by a pressure transducer. The shear force applied in the lower box is measured by a load cell and its horizontal movement is recorded by an internal displacement transducer. More details about the direct shear test device and a description of the test procedures may be found in Ferreira et al. (2015).

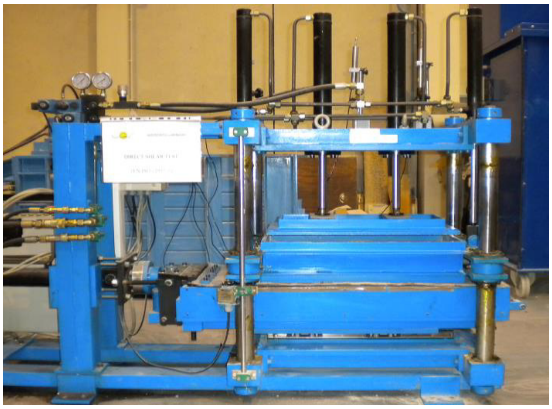


Figure 1: Direct shear test device

2.2 Materials

The soil used in this study was a locally available granite residual soil, which is typically found in northern Portugal and often used as backfill material for reinforced soil construction. According to the Unified Soil Classification System, this soil may be classified as SW-SM (well-graded sand with silt and gravel). Figure 2 shows the soil particle size distribution curve and Table 1 presents its main physical properties.

The geosynthetic tested was a biaxial woven geogrid composed of high modulus polyester (PET) fibers, knitted in a flat orientation and covered with a protective polymeric coating. Table 2 indicates the main physical and mechanical properties of this geogrid.

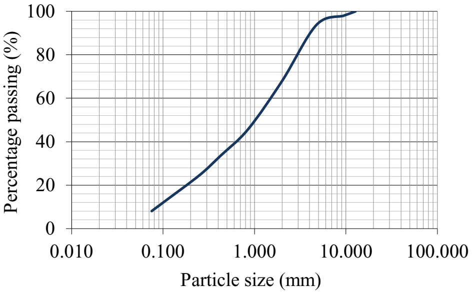


Figure 2: Soil particle size distribution curve

Property	D_{10}	D_{30}	D_{50}	C_u	C_c	G	e_{max}	e_{min}
Unit	mm	mm	mm					
Value	0.09	0.35	1.00	16.9	1.0	2.73	0.998	0.476

Table 1: Soil physical properties

Property	Mass per unit area	Mean grid size	Tensile strength, T	Peak strain, ε^T	Secant stiffness, $J_{\varepsilon=5\%}$	Raw material
Unit	g/m^2	mm	kN/m	%	kN/m	
Value	380	25×25	43.9	7.9	401.6	PET

Table 2: Physical and mechanical properties of the geogrid

2.3 Test Programme

Table 3 summarises the cyclic direct shear tests conducted on the granite residual soil-geogrid interface. In these tests, the interface was subjected to 40 cycles of sinusoidal displacement with a predetermined semi-amplitude (Δ_a) and frequency (f), under the normal stress (σ_n) of 100 kPa. To analyse the influence of the loading frequency on the soil-geogrid interface behaviour, two frequencies were adopted: 0.05 and 0.5 Hz. The effect of the strain level was also evaluated by selecting three different values of displacement semi-amplitude: 1, 5 and 10 mm. The soil was compacted to initial dry unit weights (γ_d) of 15.3 and 17.3 kN/m^3, in order to simulate different in situ compaction conditions.

The interface behaviour after cyclic loading was investigated by performing a monotonic direct shear test immediately following each cyclic test. The results from the post-cyclic direct shear tests were compared with those obtained from monotonic tests carried out on intact specimens.

Cyclic test	σ_n (kPa)	γ_d (kN/m^3)	n	Δ_a (mm)	f (Hz)
C1	100	15.3	40	1	0.5
C2	100	17.3	40	1	0.5
C3	100	17.3	40	1	0.05
C4	100	17.3	40	5	0.5
C5	100	17.3	40	10	0.5

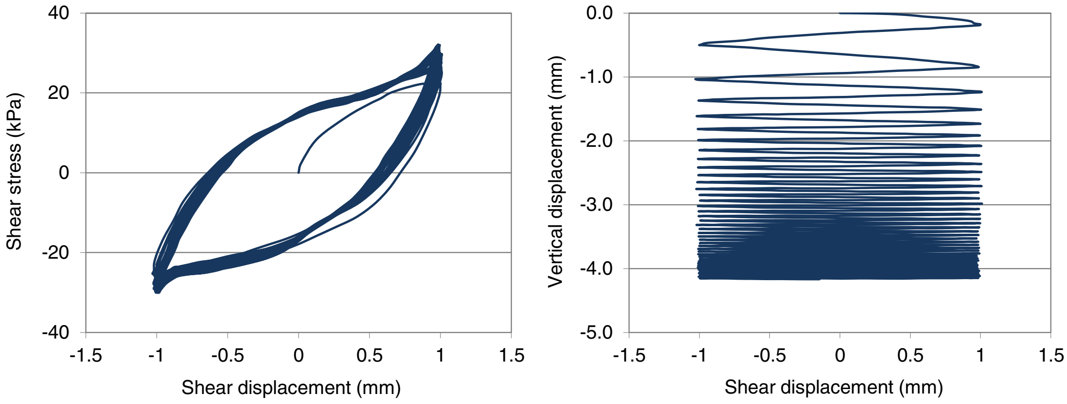
Table 3: Cyclic direct shear test programme

3 Results and Discussion

3.1 Cyclic Direct Shear Tests

Figure 3 presents the results from the cyclic direct shear test C1. In this test, the interface between the granite residual soil (compacted to the dry unit weight of 15.3 kN/m^3) and the biaxial geogrid was subjected to 40 loading cycles with frequency of 0.5 Hz and displacement semi-amplitude equal to 1 mm, under the normal stress of 100 kPa (see Table 3). Figure 3(a) shows the shear stress versus shear displacement loop curves. Figure 3(b) illustrates the evolution of the vertical displacement of the rigid plate center.

From the presented results it is possible to conclude that the mobilised shear stress increased markedly from the first to the second loading cycle. The mean value of the semi-amplitude of the shear stress achieved during the test was about 28.9 kPa (Figure 3a). It can also be observed that the vertical settlement of the soil induced by the cyclic loading was particularly significant during the first cycles, exhibiting a progressively decreasing rate throughout the test, similar to the volume change behaviour of soils under simple shear cyclic loading reported by other authors (e.g. Silver and Seed 1971). At the end of the test, the cumulative displacement of the rigid plate center was about 4.2 mm (Figure 3b).

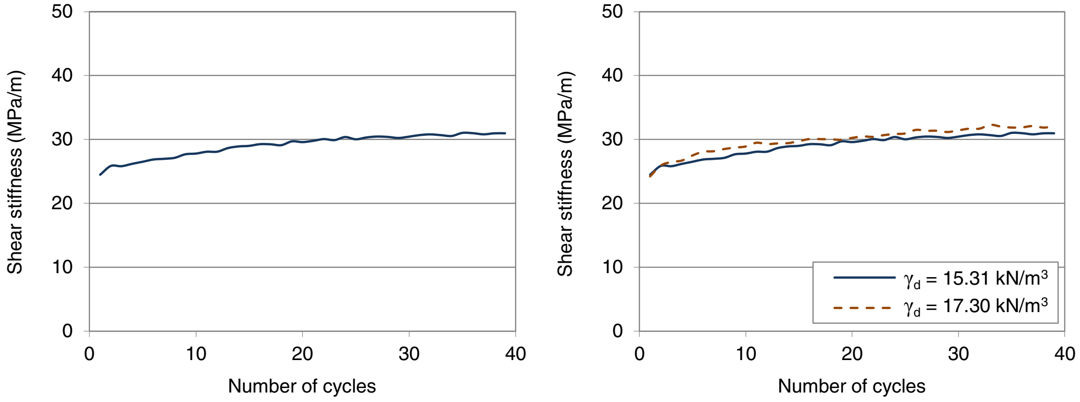


a) b)

Figure 3: Results of the cyclic direct shear test C1: a) shear stress versus shear displacement; b) vertical displacement versus shear displacement

Based on the values of the maximum shear stress and corresponding shear displacement, minimum shear stress and corresponding shear displacement for each hysteretic cycle, the secant interface shear stiffness was estimated. Figure 4(a) shows the variation of the interface shear stiffness along the cyclic direct shear test C1. It is possible to notice that the shear stiffness increased progressively during the test, which indicates that the interface response hardened with the number of cycles. However, the stiffness increase was more pronounced during the first 20 cycles, which may be associated with a more relevant soil densification at the initial stage of the test.

A comparison of the interface shear stiffness in the cyclic tests performed with looser and denser soil samples (tests C1 and C2) is presented in Figure 4(b). The effect of the placement dry density of the soil on the soil-geogrid interface shear stiffness was found to be almost negligible. However, it should be noted that, for lower normal stress values (e.g. 50 kPa), the influence of soil density on the soil-geogrid interface shear stiffness may be much more significant (Ferreira 2015). This evidence may be justified by the fact that the higher the normal stress value, the smaller the difference between the dry density of looser and denser soil samples after the application of the normal load.



a) b)

Figure 4: Evolution of the interface shear stiffness with the number of loading cycles: a) cyclic direct shear test C1; b) influence of soil density on the soil-geogrid interface shear stiffness (tests C1 and C2)

The influence of the loading frequency and semi-amplitude of shear displacement on the soil-geogrid interface shear stiffness is illustrated in Figures 5(a) and 5(b), respectively. Figure 5(a) reveals that, regardless of the frequency adopted (i.e. f = 0.5 Hz, test C2, or f = 0.05 Hz, test C3), the interface stiffness increased slightly with the number of loading cycles. During the first cycles, the interface stiffness was slightly higher in the test performed with lower frequency. However, the effect of the frequency of the sinusoidal waves on the interface shear stiffness tended to dissipate throughout the cyclic loading. After 10 loading cycles, the interface stiffness was almost coincident in the tests carried out with different frequencies. Therefore, it can be concluded that the cyclic behaviour of the interface was not significantly affected by the loading frequency (for the values herein considered).

As shown in Figure 5(b), the interface shear stiffness decreased significantly with increasing displacement semi-amplitude. The mean values of the interface shear stiffness were about 30.0, 17.5 and 11.6 MPa/m in the cyclic tests conducted with semi-amplitudes of 1, 5 and 10 mm (tests C2, C4 and C5), respectively. The curves presented in Figure 5(b) also indicate that the variation of the shear stiffness decreased with increasing semi-amplitude of the shear displacement, which is in agreement with the results reported by Vieira et al. (2013) for a sand-geotextile interface.

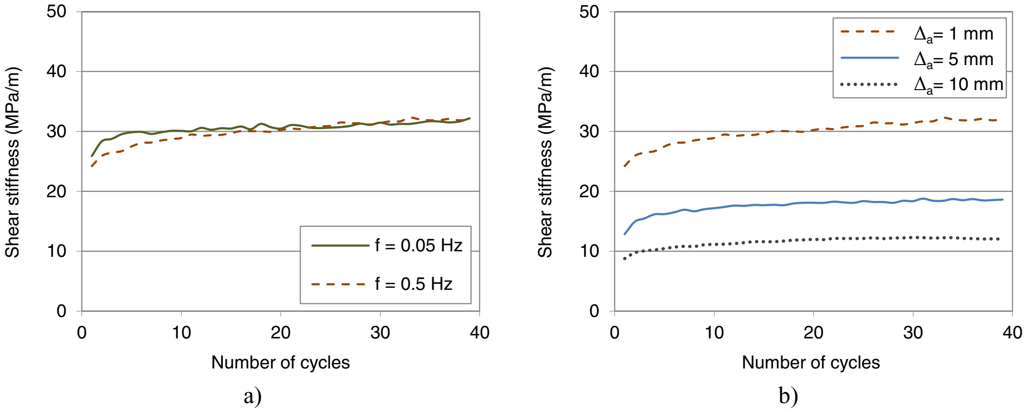


Figure 5: Evolution of the interface shear stiffness with the number of loading cycles: a) influence of loading frequency (tests C2 and C3); b) influence of displacement semi-amplitude (tests C2, C4 and C5)

3.2 Post-cyclic Direct Shear Tests

As previously mentioned, the post-cyclic interface behaviour was investigated by performing direct shear tests under monotonic loading conditions following the cyclic tests. Figure 6 compares the results from the monotonic test carried out after the cyclic test C1 with those obtained from monotonic tests on fresh specimens, in terms of the shear stress-shear displacement relationship (Figure 6a) and the vertical displacement of the rigid plate center (Figure 6b). The effect of cyclic loadings with different values of frequency and displacement semi-amplitude on the post-cyclic interface response is shown in Figures 7 and 8, respectively.

Figures 6(a), 7(a) and 8(a) demonstrate that the cyclic loading did not lead to the degradation of the interface shear strength. After cyclic tests with higher displacement semi-amplitudes (5 and 10 mm), the interface peak shear strength exceeded the values obtained from the reference monotonic tests, which may be related to a more relevant increase in soil density induced by the loading cycles.

Regarding the deformation of the specimens throughout the tests, it can be concluded that, in the post-cyclic direct shear tests, the vertical contraction tended to reduce, whereas the expansive behaviour of the soil tended to be more pronounced, when compared with that observed in the monotonic direct shear tests conducted on intact specimens (Figures 6b, 7b and 8b).

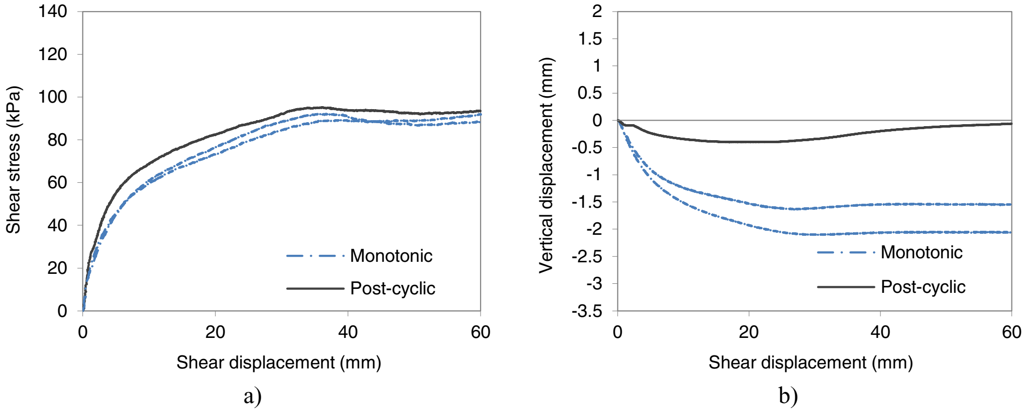
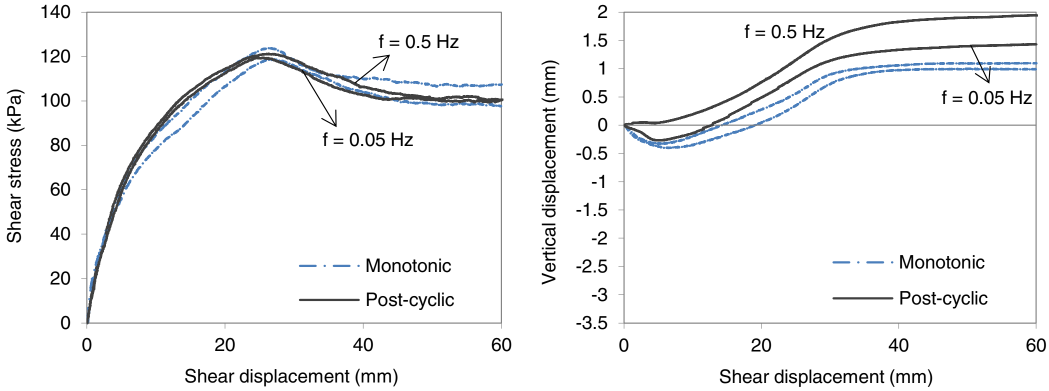
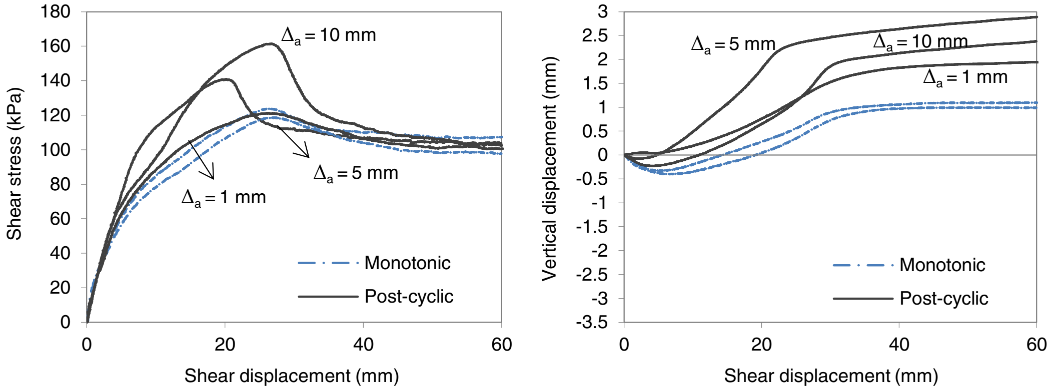


Figure 6: Influence of cyclic loading on the soil-geogrid interface behaviour (after cyclic direct shear test C1): a) shear stress versus shear displacement; b) vertical displacement versus shear displacement



a) b)

Figure 7: Influence of cyclic loading on the soil-geogrid interface behaviour (after cyclic direct shear tests C2 and C3): a) shear stress versus shear displacement; b) vertical displacement versus shear displacement



a) b)

Figure 8: Influence of cyclic loading on the soil-geogrid interface behaviour (after cyclic direct shear tests C2, C4 and C5): a) shear stress versus shear displacement; b) vertical displacement versus shear displacement

4 Conclusions

This paper presented the results of cyclic and post-cyclic (monotonic) direct shear tests on a granite residual soil-geogrid interface. The influence of soil density, loading frequency and displacement semi-amplitude on the secant interface shear stiffness was examined. A comparison between the results from post-cyclic direct shear tests and those obtained from monotonic tests on fresh specimens was then established, enabling the assessment of the effect of cyclic loading on the interface behaviour during shearing. The main conclusions of this study are summarised below.

No relevant influence of the placement dry density of the soil on the soil-geogrid interface shear stiffness during the cyclic loading was observed.

The influence of the frequency of the sinusoidal waves on the shear stiffness of the studied interface was almost negligible.

The soil-geogrid interface shear stiffness reduced as the semi-amplitude of the shear displacement increased. This reduction was more significant for lower values of displacement semi-amplitude.

Regardless of the soil density, loading frequency and displacement semi-amplitude, no degradation of the interface shear strength was observed after the cyclic direct shear tests.

The post-cyclic peak shear strength of the interface increased significantly with the displacement semi-amplitude, which may be related to the fact that the soil densification induced by the cyclic loading became more relevant as the value of the semi-amplitude was increased.

As a result of the increase in soil density induced by the previous cyclic loading, the vertical contraction of the soil samples during the post-cyclic direct shear tests tended to be less significant than that observed in the monotonic direct shear tests conducted on intact specimens, whereas the soil dilation tended to be more pronounced.

Acknowledgements

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