Experimental Investigation of Mechanical Damage in Geogrids

Ana Cristina C.F. Sieira, Alberto S.F.J. Sayão

Abstract. This paper presents the results of a comprehensive experimental program for investigating the influence of mechanical damage on the load-displacement behavior of geogrids. Unconfined tension tests, pullout and direct shear tests were carried out on intact and damaged specimens. Natural or artificial damages were produced either by imposing heavy compaction procedures in the laboratory or by simply cutting one or more geogrid elements. It is concluded that natural damage in the geogrid may be more pronounced when aggressive compaction methods are used with coarse grained soils. Fine grained soils did not show a significant strength reduction even when subjected to heavy compaction in the laboratory. Under pullout loading, artificial damage was also noted to be of little significance for fine soil (silty clay). Rupture of the geogrid's transverse elements led to a significant pullout strength reduction. These transverse elements are responsible for anchoring the geogrid within the soil mass. However, under unconfined tensile load, these transverse elements are responsible only for the grid's geometrical configuration and their rupture did not induce a significant strength loss. In direct shear, the position of the geogrid relative to the potential failure surface was shown to be an important factor.

Key words: geogrids, mechanical damage, laboratory shear tests.

1. Introduction

1.1. Mechanical damage regarding design

In geosynthetic reinforced soil masses, allowable tensile stress of the reinforcement is determined by reducing its characteristic strength by a global reduction factor. This characteristic strength is obtained from basic characterization tests, regardless of the geosynthetic environmental and constructional loading conditions.

The global reduction factor is usually decomposed in partial factors for considering the independent reductions of geosynthetic properties due to installation process (mechanical damage), chemical and biological degradation, connections between adjacent mats, and time dependent (creep) deformations.

In reinforced masses, the mechanical damage is the main partial factor influencing the global reduction factor. The geosynthetic material may suffer severe installation damage due to handling, contact with sharp edged soil or rock grains, compaction and traffic surcharge. These factors may induce severe reductions in the mechanical properties of the geosynthetic material.

Paulson (1990) reports on another type of mechanical damage, imposed by the initial loading characteristics, after compaction is completed. Damage occurring during the installation process may alter significantly the geosynthetic mechanical properties. The reduction factor due to mechanical damage is usually determined by the ratio between the strength magnitudes from intact and damaged specimens. Specimens with natural construction damage may be obtained by exhumation immediately after installation and compaction.

The damage intensity depends on the installation process and on the soil type in contact with the geosynthetic material. When used as pavement reinforcement, the geosynthetic may suffer intense installation damages in contact with sharp grained granular material under high compaction efforts. These damages may well be of higher magnitudes than in the case of geosynthetic reinforced fills placed under low compaction over fine grained soft soils.

Determination of reduction factor f_R due to mechanical damage is subject to controversy, due to the large number of variables to be considered. As a consequence, a variety of laboratory procedures have been proposed to simulating damage conditions observed in field installation.

A standard procedure for duplicating severe geosynthetic damage during installation in granular materials has been proposed (ISO 1998). The geosynthetic specimen is to be placed between layers of soil or aggregate. Damage is imposed by intense vibration of 200 cycles of 900 kPa compressive load, under a frequency of 1 Hz. The damaged material is then tested and its mechanical or hydraulic behavior is observed.

Christopher & Holtz (1984) tried to quantify the reduction factor f_R due to mechanical damage, relating the strength loss of the geosynthetic to its surviving capacity and to the severity of ambient conditions during installation. The authors suggest three categories (low, moderate or high) for the surviving capacity of geotextiles, according to its structural and mechanical characteristics.

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Rainey & Barsdale (1993) classify the geogrids under two main categories: flexible (woven grids) and stiff (polyethylene or polypropylene non-woven grids). Wrigley (1987) and Troost & Ploeg (1990) proposed classification criteria for the surviving capacity of geogrids based on the short term tensile strength. Allen (1991) and Azambuja (1994) suggest restricting the expression "surviving capacity" for describing only the geosynthetic's resistance against severe damage upon construction efforts and initial loading. When relating to installation conditions, these authors suggest the expression "ambient severity". The classification criterion is summarized in Table 1.

Allen (1991) also proposed a classification for severity of compaction conditions in reinforced soil retaining systems (Table 2). This classification depends on three main factors: compaction equipment, shape and dimensions of soil grains and thickness of the compacted soil layer over the geosynthetic material.

1.2. Mechanical damage regarding experimental tests

Testing programs for evaluating the effect of mechanical damage on geosynthetic behavior have been reported by several authors. In most cases, the strength loss was measured by rating the tensile strengths of intact and naturally damaged specimens. These damaged specimens were exhumed after real construction procedures (Koerner & Koerner, 1990), or after experimental field work (Bush, 1988; Wrigley, 1987; Troost & Ploeg, 1990; Koerner & Koerner, 1990; Allen, 1991; and Azambuja, 1994).

Tensile tests reported by Bush (1988) on stiff HDPE (high density polyethylene) geogrids showed a strength loss of about 4 to 8% under low severity conditions, and from 12 to 17% under moderate severity.

For tests on stiff polyester geogrids, Wrigley (1987) showed a strength loss of 5 to 10% under low severity and of 30 to 40% under high severity condition. On the other hand, Troost & Ploeg, (1990) reported that, when coated with a PVC layer, polyester geogrids exhibited a much lower strength loss (about 13%), even tested under highly severe conditions.

Tests on specimens exhumed after real construction showed that stiff HDPE geogrids did not loose strength under low severity conditions. However, both non-woven polyester and woven polypropylene geotextiles did show a significant loss of about 15%, under similar installation conditions (Koerner & Koerner, 1990).

Viezee *et al.* (1990) concluded that a localized mechanical damage does not alter significantly the average deformation of synthetic fibers. Although the strength may be reduced by the necking observed in the transverse section, the damaged fiber does maintain its stiffness.

Experimental field investigation carried out by Allen (1991) showed strength losses as high as 40% for polypropylene or polyester woven geotextiles exhumed after

Table 1 - Classification for surviving capacity of geosynthetics (Azambuja, 1994).

Surviving capacity	Geotextile		Geogrid	
	Woven	Non-woven	Flexible	Stiff
Low	$M_A \leq 135$	$M_A \leq 135$	-	-
Moderate	$135 < M_A \leq 150$	$135 < M_A \leq 200$	$T \leq 55$	$T < 55$
High	$M_A > 150$	$M_A > 200$	$T > 55$	$T \geq 55$

Legend: M_A = mass per area or gramature (g/m^2); T = tensile strength (kN/m^2).

Table 2 - Classification for ambient severity (Allen, 1991).

Compaction equipment	Filling material	Ambient severity		
		$t < 15$ cm	$15 < t < 30$ cm	$t > 30$ cm
Light	Fine to coarse sand with rounded grains	Low	Low	Low
	Well graded sand and cobbles with sub-rounded to sub-angular grains ($D_{max} < 75$ mm)	Moderate	Low	Low
	Poorly graded cobbles with angular grains ($D_{max} < 75$ mm)	Very high	High	Moderate
Heavy	Fine to coarse sand with rounded grains	Moderate	Low	Low
	Well graded sand and cobbles with sub-rounded to sub-angular grains ($D_{max} < 75$ mm)	High	Moderate	Low
	Poorly graded cobbles with angular grains ($D_{max} < 75$ mm)	-	Very high	High

Legend: D_{max} = maximum grain size. t = thickness of compacted soil layer.

construction under moderately severe conditions. Troost & Ploeg (1990) also tested woven polyester geotextiles and reported a strength loss of 7 to 15% for low severity, and of 12 to 25% for moderate severity. For strength losses under 10%, these authors observed that the exhumed material may have an initial stiffness slightly above than that of intact material. This fact may be due to the previous tensile surcharge induced by compaction.

Geosynthetic material is commonly positioned between two soil layers of similar characteristics. In uniform soils with angular particles, mechanical damage results from high contact stresses due to compaction efforts (Fig. 1).

Lopes (2000) reported pullout test results in artificially damaged geogrid specimens, under several confining stress levels. Damage was imposed by cutting selected grid elements. Nine different configurations of grid damages have been tested. Lightly damaged specimens reach the peak strength under pullout conditions. Highly damaged specimens fail by tension in a localized position of the grid. The pullout strength ratio for intact and damaged specimens was observed to increase with increasing confining stress levels.

Confined tension tests in non-woven geotextiles, immersed in sand or coarser materials, were reported by Azambuja (1999). Under low compaction energy, the confined strength value may be lower than the unconfined one. This difference is smaller for high confining levels. However, under intense compaction, the confined strength is significantly higher than the unconfined one, emphasizing the beneficial effect of confinement on the behavior of damaged specimens.

Damage reduction factors are usually defined from unconfined tension test results. However, geosynthetic materials in field applications are frequently immersed in a soil mass. Confined tests would therefore reproduce more closely the geosynthetic conditions in reinforced fills.

This paper aims at evaluating the effect of mechanical damage on the load-elongation behavior of geogrids, taking into account its interaction mechanism with the confining soil. A comprehensive testing program was carried out in the laboratory, including unconfined tension, pullout and direct shear tests in damaged specimens.

Two different types of damages were herein considered:

1) Natural damage, resulting from laboratory simulations of field installation and compaction; it may or may not cause the rupture of the grid element, depending upon the severity of the compaction process.

2) Artificial damage, imposed by physical rupture by cutting one or more grid element with a scissor.

2. Materials

The experimental program made use of one specific type of geogrid and three distinct types of soil. The geogrid is commercially known as MacGrid 11/3-W and exhibits a regular woven mesh, made of stiff polyester filaments, coated by PVC for protection against installation and operational damages. The geogrid has a tensile strength of 92.4 ± 2.2 kN/m in longitudinal direction and of 29 ± 0.5 kN/m in transverse direction.

The grid geometry may be defined by a square opening of 20 mm (Fig. 2) and a solid surface area percentage of 30%, which is available for soil-geogrid friction.

The three soils had very distinct grain size distributions: silty clay, sand and cobble. The silty clayey soil is composed by 60% of clay minerals: kaolinite, chlorite and smectite. The remaining 40% is made of quartz and feldspar. The sandy soil is predominantly composed by quartz and feldspar. The coarser material (cobble) is made of basaltic rock fragments with 20 mm of average diameter (Fig. 3).

The main geotechnical characteristics of these three soils are presented in Table 3, in which G_s is the specific gravity and LL and PL are respectively the liquid and the plastic limits. Values of effective cohesion (c') and friction angle (ϕ') were obtained from direct shear tests on 300 mm x 300 mm specimens (Sieira, 2003). The sand was tested under a relative density D_r = 80%, while silty clay specimens were prepared at Proctor's optimum water content and 100% compaction degree.

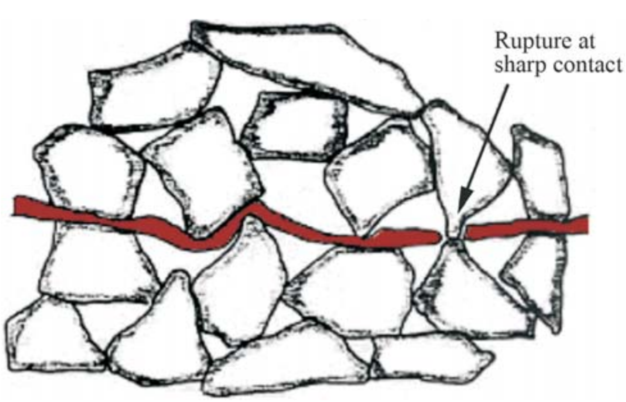


Figure 1 - Damage mechanism in geosynthetic used as reinforcement (Azambuja, 1994).

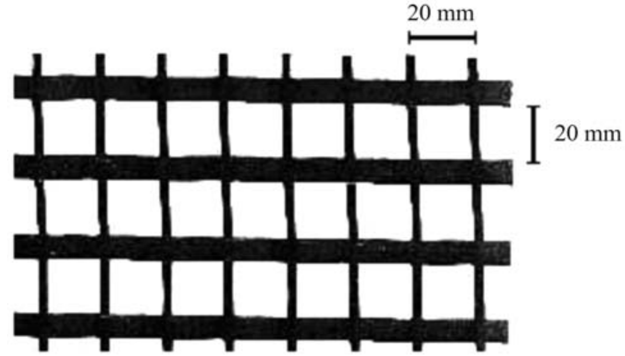


Figure 2 - Geogrid geometry.

Figure 3 - Basalt cobble.

3. Experimental Program

Unconfined tension, direct shear and pullout tests were performed on intact and damaged specimens in the CEDEX laboratory, in Spain (Sieira & Sayão, 2006). Two types of damage have been considered: natural damage, resulting from simulations of compaction procedures, and artificial damage, imposed by physically rupturing selected grid elements.

3.1. Unconfined tension tests: naturally damaged specimens

A 300 mm square metallic box, 150 mm in height, has been used for mechanical damage simulations. Initially, a 75 mm thick soil layer was compacted in the lower half of the box. The geogrid was then positioned (Fig. 4a) and the soil specimen was compacted in the upper half. Two distinct compaction procedures have been considered: a light compaction with an energy level similar to the Modified Proctor (2.63 J/cm^2), using a 4.5 kg manual hammer; and a stronger compaction (10.52 J/cm^2), using a dynamic vibrator.

After compaction, the geogrid specimens were carefully exhumed, avoiding additional damage, and then subjected to detailed microscopic inspection before taken to tension tests in the laboratory.

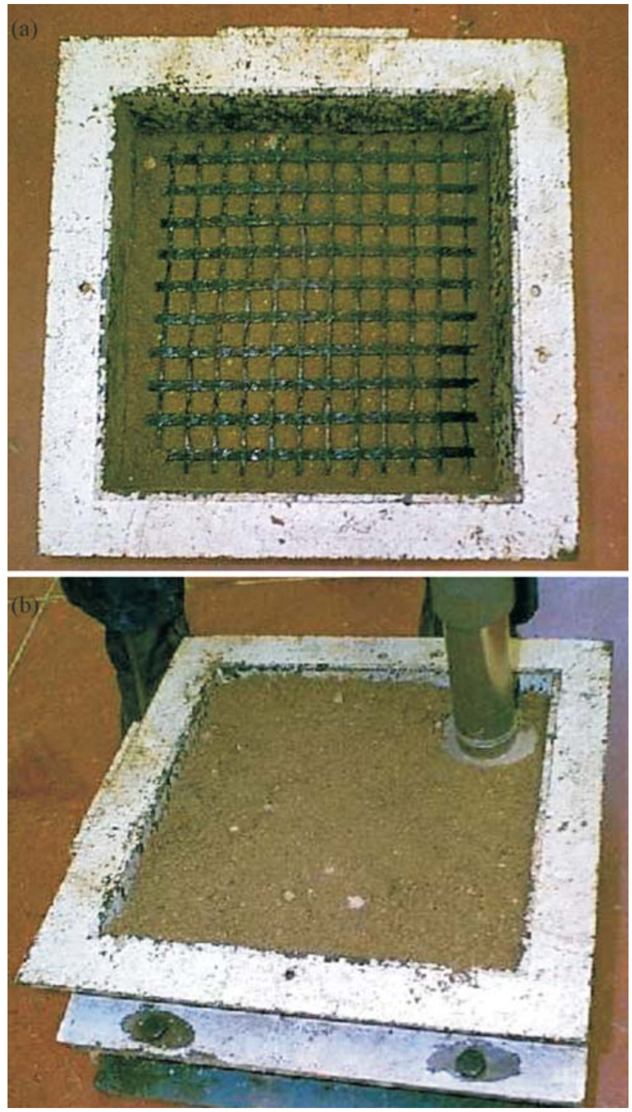


Figure 4 - Experimental simulation of mechanical damage on geogrid. (a) positioning the geogrid; (b) compacting with a manual hammer.

The mechanical damage was evaluated by a reduction factor (f_d), defined as:

$$f_d = \frac{\text{intact strength}}{\text{exhumed strength}} \tag{1}$$

Table 3 - Geotechnical characteristics of soils.

Soil type	Physical characteristics			Strength parameters	
	G_s	LL (%)	PL (%)	c' (kPa)	ϕ' (°)
Silty clay (at w_{ot})	2.69	29.7	19.0	30	21
Sand (D_r = 80%)	2.71	-	-	16	37

3.2. Unconfined tension on artificially damaged specimens

Unconfined tension tests on artificially damaged specimens were carried out to evaluate the strength loss resulting from intense damage caused by cutting one or more mesh elements. All geogrid specimens were 200 mm wide and 250 mm long, ensuring an effective length of 100 mm between opposing claws. Tensile loading was imposed under a speed of 20 mm/min.

An Instron loading equipment was provided with claws according to the European and Brazilian standards for geotextile's tensile properties by wide-width strip method (ABNT, 1993).

Six intact geogrid specimens were used in these tension tests. Artificial damage was imposed after positioning the specimens in the loading device, without pre-tensioning. Three specimens had their central transverse elements cut (ruptured), as indicated in Fig. 5a. The other 3 specimens were cut in the central longitudinal element (Fig. 5b).

3.3. Pullout testing on artificially damaged specimens

These tests were carried out on 1 m square specimens in a large shearing apparatus. Artificial damage was imposed by cutting one or more mesh elements with a scissor.

The device was initially developed for direct shear tests on soils and rockfill and later modified for pullout testing of geosynthetics (Sayão *et al.*, 2002; Sieira *et al.*, 2009).

Initially, the lower half of the box was filled with compacted layers of soil. The damaged geogrid was then positioned and fixed to the claw, before the soil layers were statically compacted in the upper half. The confining pressure was then imposed and the pullout load applied.

During the tests, load and displacement were carefully monitored at the tensional claw, which was positioned at 20 cm distance from the frontal face of the device.

Table 4 presents the pullout testing program. Geogrid specimens with different damage configurations were considered for allowing direct comparison with intact grids.

The experimental program consisted of tests on specimens with 3 or 5 damaged elements, distributed along the

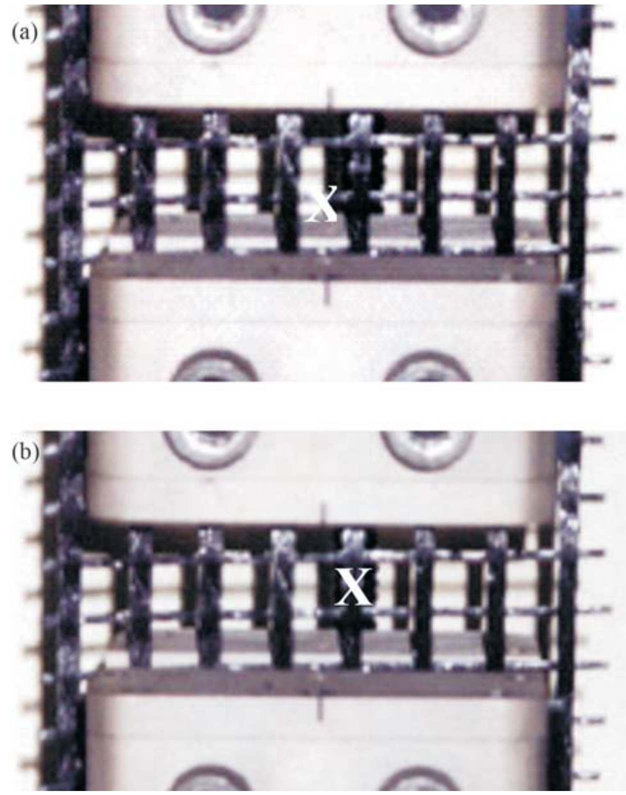


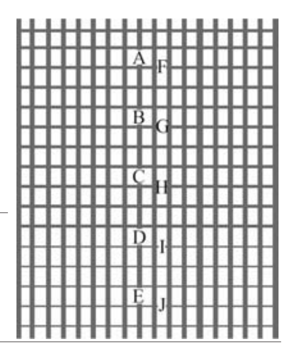
Figure 5 - Position of damaged geogrid elements. (a) transverse element; (b) longitudinal element.

central longitudinal element. The damage was imposed by rupturing the longitudinal mesh elements, along the pullout direction (points A, B, C, D and E).

In sandy soil, tests were also carried out on specimens with damages in the transverse direction, distributed along the pullout direction (points F, G, H, I and J). These tests aimed at evaluating the contribution of transverse elements under pullout loading. All tests on damaged specimens were performed under a confining pressure of 25 kPa.

It should be noted that, under a pullout load, longitudinal strips are mainly responsible for mobilizing friction at soil's interface. Transverse elements are responsible for

Table 4 - Pullout tests in artificially damaged specimens.

Soil	N. of damages	Grid element	Damage	Damage position
Sand	0	-	-	
	3	Transverse	G H I	
	5	Transverse	F G H I J	
	3	Longitudinal	B C D	
	5	Longitudinal	A B C D E	
Silty clay	0	-	-	
	3	Longitudinal	B C D	
	5	Longitudinal	A B C D E	

mobilizing passive loads due to geogrid's anchoring within the confining soil. The damage distribution along the longitudinal or transverse strips helped in evaluating the worst damage position along the reinforcement.

The reduction factor for mechanical damage is usually computed from the ratio of intact over damaged strengths, under unconfined tensile conditions. The pullout tests were carried out for finding out the strength loss under confined conditions, which is a common situation in the field.

3.4. Direct shear testing on artificially damaged specimens

The experimental program included direct shear tests on damaged specimens, placed vertically inside the shear box. These tests allowed the investigation of the influence of damage in situations where the failure surface intercepts the reinforcement. In this case, the geogrid becomes tensioned and lends a positive tensile strength to the soil.

These tests were carried out with a shear box of 300 mm x 300 mm, in sandy and silty-clayey soils under a confining level of 100 kPa. The geogrid's position in the shearing box is shown in Fig. 6. The damage was imposed in the longitudinal central strip of the specimen, at the position of the imposed shear plane. The sandy soil was prepared with 10% water content and a relative density of 80%. The silty clay was compacted at optimum water content, reaching a compaction degree of 100%. These conditions were similar to those adopted in pullout and direct shear testing on natural unreinforced soils.

All shearing tests in the 300 mm x 300 mm box followed the ASTM D5321 requirements about the minimum dimension of the box being at least five times larger than the geogrid's openings.

4. Results

Damage effects were evaluated by different tests (unconfined tension, pullout, direct shear) and different types of damage (natural or artificial) imposed to the geogrid specimens. The nomenclature convention adopted for the reduction factors is presented in Table 5. These reduction factors were obtained from the ratio between intact and damaged specimens (Eq. (1)).

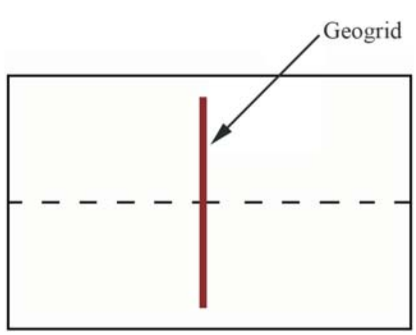


Figure 6 - Position of geogrid inside the direct shear box.

4.1. Unconfined tension on naturally damaged specimens

Table 6 presents the results of reduction factors ($f_d = f_{d1}$) from unconfined tension tests with naturally damaged geogrid specimens. Values of f_{d1} were computed from the ratio between intact and damaged tensile strengths (Eq. (1)). The results indicated a significant strength loss when the compacted cobble was used, with reduction factors from 1.30 (light compaction) to 1.45 (strong compaction).

In sand, strong compaction imposed a reduction factor of only 1.07, while light compaction was insignificant in damaging the geogrid. The compacted silty clay did not suffer any strength loss due to compaction procedures.

Intact geogrid had a tensile strength of 92.4 kN/m, slightly lower than the manufacturer's nominal value of 97 kN/m. This difference may be due to changes in testing procedures, in particular those related to the fixing details of the geogrid (Sieira *et al.*, 2006).

Microscope inspection revealed that, in compacted cobble, the core polyester phylaments were ruptured beyond the PVC coating protection, as indicated in Fig. 7. This is important because the core is responsible for the mechanical characteristics of the geogrids. The function of the coating is to protect the core against damages due to installation and to the use of the reinforced structure. Damage in the core may therefore cause a significant strength loss.

On the other hand, damage on the coating may cause long term problems, as the core is exposed to chemical and biological actions during the operational life of the reinforced mass.

Table 5 - Symbols for reduction factors.

Damage	Test	Reduction factor
Natural	Unconfined tension	f_{d1}
Artificial	Unconfined tension	f_{d2}
	Pullout	f_{d3}
	Direct shear	f_{d4}

Table 6 - Redution factors of geogrids damaged by compaction.

Soil	Compaction	Tensile strength (kN/m)	Factor f_{d1}
Silty clay	Light (2.63 J/cm^2)	92.1	1.00
Sand	Light (2.63 J/cm^2)	92.0	1.00
Cobble	Light (2.63 J/cm^2)	70.1	1.30
Silty clay	Strong (10.52 J/cm^2)	92.0	1.00
Sand	Strong (10.52 J/cm^2)	86.5	1.07
Cobble	Strong (10.52 J/cm^2)	63.5	1.45

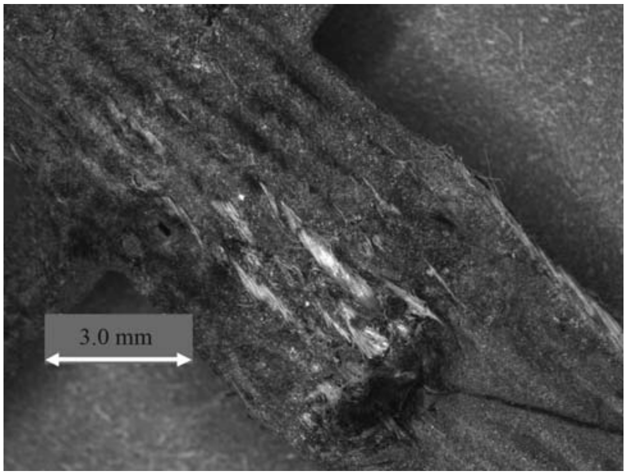


Figure 7 - Microscope inspection of natural damage after laboratory compaction.

4.2. Unconfined tension on artificially damaged specimens

Tests in naturally damaged specimens show that the compaction procedures herein considered did not cause severe damage to the geogrids in fine to medium grained soils (clay or sand). Additional tension tests were then carried out on specimens with intense damage, imposed by rupturing the grid elements with a special scissors.

The reduction factors ($f_d = f_{d2}$) obtained under unconfined conditions are presented in Table 7. The tensile strength of undamaged geogrid is 92.4 kN/m in the same longitudinal direction. Three identical tension tests were performed on specimens with one cut longitudinal element and another three tests were done on specimens with one cut in a transverse element.

Typical results are presented in Fig. 8. As longitudinal elements are responsible for transferring the tensile load along the geogrid, a significant drop in strength is to be expected when one or more of these elements are breached. Rupture of a longitudinal element caused a strength reduction of about 21%, corresponding to a factor f_{d2} = 1.27.

On the other hand, under unconfined tensile loads, transverse elements are mainly responsible for the positioning and configuration of the mesh. Accordingly, the strength reduction was of 9,6%, which corresponds to a factor f_{d2} = 1.11. However, in pullout loading, these elements are responsible for anchoring the grid in the soil mass and the contribution of passive resistance to the overall strength becomes more significant (Jewell *et al.*, 1984).

Figure 9 presents two geogrids after unconfined tension tests. It is noted that failure of the mesh happens at the contact position with the claws. These therefore represent a week point in the testing arrangement and may be responsible for differences in results from tests in different devices.

Table 7 - Unconfined tension tests along longitudinal direction on artificially damaged geogrid.

Ruptured element	Tensile strength (kN/m)	Average	f_{d2}
	74.0		
Longitudinal	72.0	72.8	1.27
	72.5		
	80.0		
Transverse	84.0	83.5	1.11
	86.5		

4.3. Pullout testing on artificially damaged specimens

Reduction factors are usually computed from laboratory tension tests, in which the geogrid is kept unconfined. In the field, however, the geogrid is immersed in the soil mass. Other variables become therefore relevant, such as confining stress, soil type, soil density and grid geometry.

Confined tests reproduce more appropriately the field operational conditions of geogrids within reinforced soil masses. Consequently, reduction factors due to damage shall be more adequately investigated from confined pullout tests.

Table 8 presents the results of pullout tests and corresponding reduction factors ($f_d = f_{d3}$). Factor f_{d3} was computed from the ratio between intact and damaged pullout strengths, in a similar way as previously defined for tension tests.

Pullout results for dense sand (D_R = 80%) are presented in Fig. 10. These results correspond to damages along one longitudinal strip. The pullout strength is seen to drop significantly with increasing number of damaged elements. It is important to note that, in these tests, the geogrid is pulled out from the soil, exposing damage A (Table 4). In this unconfined zone, a gradual increase in the longitudinal

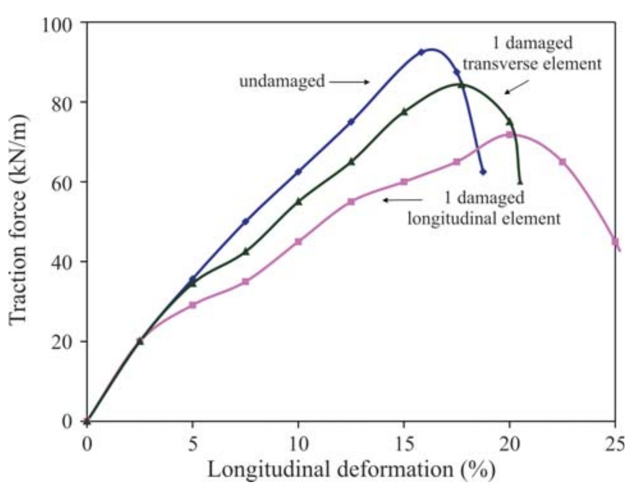


Figure 8 - Tension tests in artificially damaged geogrid specimens.

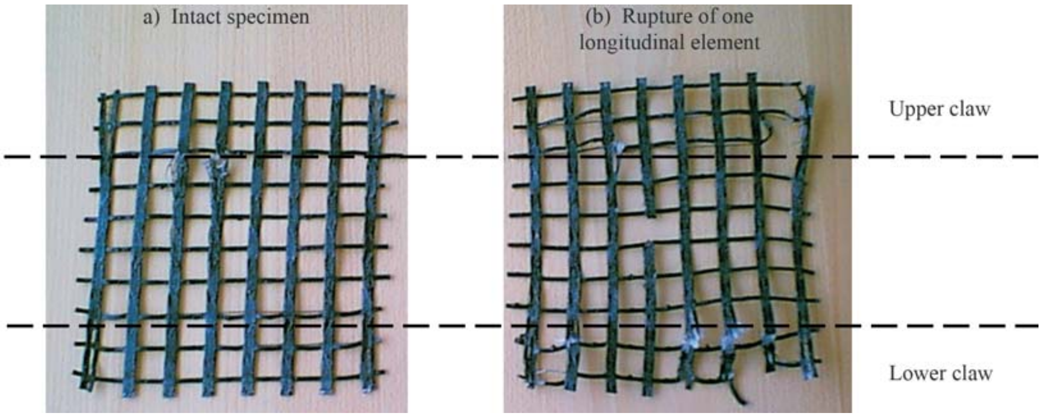


Figure 9 - Geogrid configuration after unconfined tension tests.

Table 8 - Pullout tests on artificially damaged geogrid specimens.

Soil	D_R or GC (%)	N. of damages	Damaged strip	P_{ult} (kN/m)	f_{d3}
Sand	0	0	-	65.1	-
		3	Longitudinal	49.0	1.32
		5	Longitudinal	38.2	1.70
		3	Transverse	55.8	1.16
		5	Transverse	41.9	1.55
Silty clay	100	0	-	51.5	-
		3	Longitudinal	44.1	1.17
		5	longitudinal	42.7	1.20

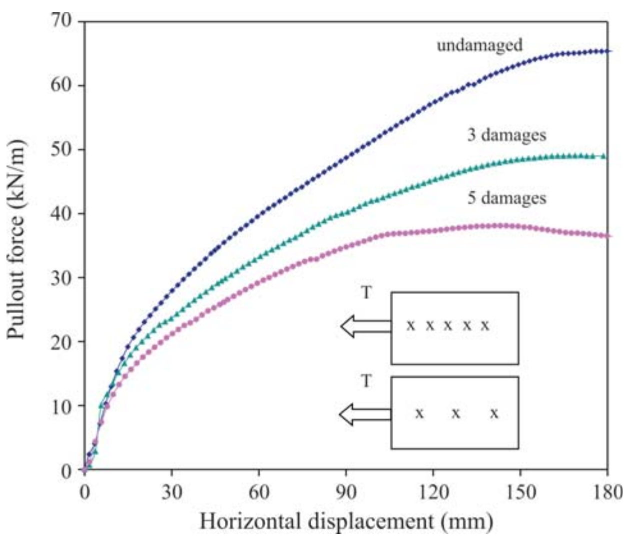


Figure 10 - Pullout tests in sand: damage in geogrid's longitudinal strip.

dimension of the damage was observed, causing a reduction of the geogrid's stiffness.

The longitudinal strip is responsible for transferring the tensional load. Damage reduces the tension stiffness and strength of the geogrid. It should be noted that the pullout displacement is composed by two main parts: deformation and rigid body displacement.

Figure 11 presents the marked variations of strength values and reduction factors with the number of damaged elements for pullout tests in sand. With increasing damage, pullout strength decreases, while factor f_{d3} increases. For five damages in the central strip, f_{d3} reaches 1.70, corresponding to a strength loss of about 42%. These results are somewhat magnified by the grid's exposure in the unconfined region, as previously discussed.

In silty clay soil, similar behavior was noted for damaged geogrids (Fig. 12). Increasing damage caused a decrease in pullout strength, although this decrease was less significant than in sand. With 5 damages, factor f_{d3} was 1.20, instead of the observed value of 1.70 in sand. This was probably related to the lower interface shearing resistance of the geogrid with silty clay, as compared to sand. These results suggest that the effect of damage is higher for coarse grained soils.

Tests results with geogrids damaged in transverse elements are presented in Fig. 13. A significant loss in strength is noted for increasing damage in transverse strips. This is in opposition to the findings drawn from unconfined tension tests, but may be explained by the relative contribution of passive resistance related to transverse elements of the geogrid during pullout loading. Experimental evidence of this passive contribution in overall pullout strength of geogrids has been presented by Palmeira (1987), Palmeira & Milligan (1989) and Sieira (2003).

Pullout tests in artificially damaged specimens had allowed the evaluation of the susceptibility of geogrids to the mechanical damage. A susceptibility index S has been defined by Eq. (2) and can be visualized by the declivity of the curve between the reduction factor and the number of damaged elements.

$$S = \left(\frac{\Delta f_{d3}}{\Delta n} \right) \times 100\% \tag{2}$$

where Δf_{d3} = variation of reduction factor and Δn = variation of number of damaged elements.

It may be noted that large values of S are related to a higher geogrid's susceptibility to loose strength due to damage.

Figure 14 shows the influence of damage in geogrids inserted in different soils (sand and in silty clay) under pullout loading. An approximately linear drop of the pullout strength in sand may be noted with increasing number of damages in a longitudinal element, resulting in a susceptibility index $S = 8.3\%$. The influence of damage is much less significant in silty clay, for which a decreasing S may be noted for increasing damage. For this clayey soil, when the geogrid goes from 3 to 5 damages the susceptibility index is noted to be $S = 1.8\%$.

This larger pullout reduction for tests of geogrids immersed in sand is related to the higher interlocking of soil grains around the geogrid mesh, as shown in pullout results with intact geogrid (Sieira & Sayão, 2004).

4.4. Direct shear testing on artificially damaged specimens

In the direct shear tests, damage was imposed by cutting one element in the central longitudinal element and the geogrid was placed in a vertical position, as illustrated in Fig. 6.

Figure 15 presents a comparison of test results with intact and damaged geogrid specimens in both sand and

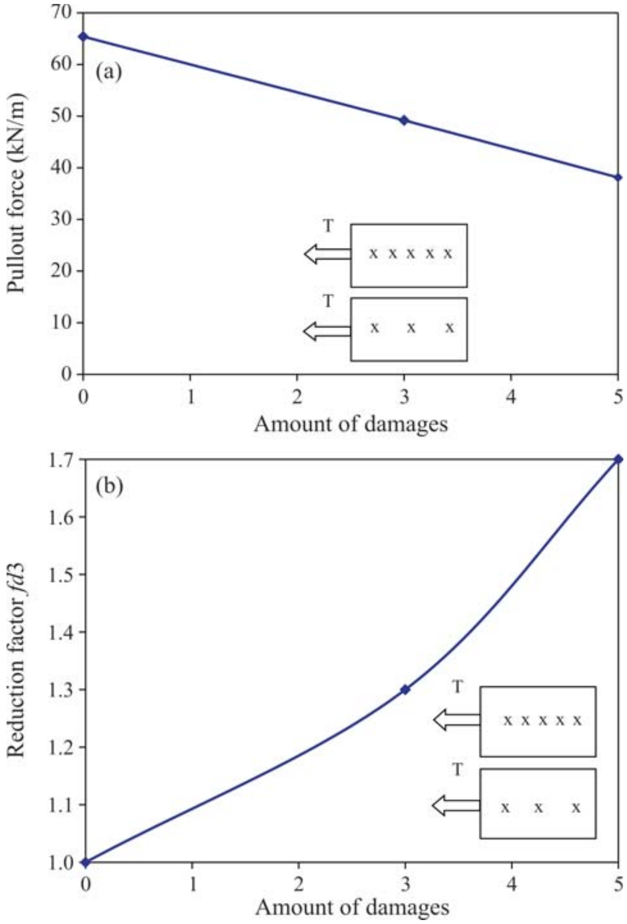


Figure 11 - Pullout tests in sand: influence of artificial damage in longitudinal direction. (a) pullout strength; (b) reduction factor f_{d3}.

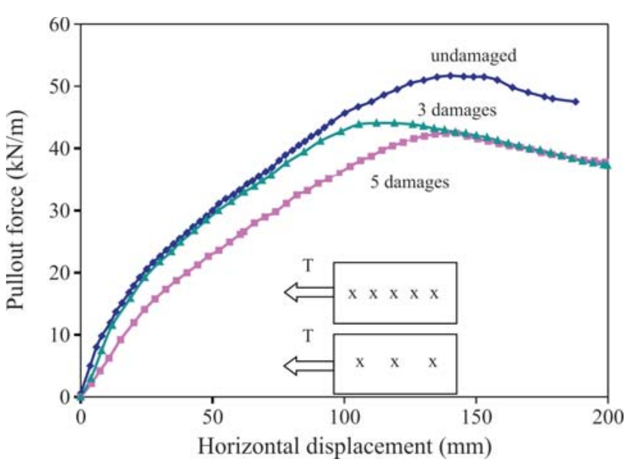


Figure 12 - Pullout tests in silty clay: damage in geogrid's longitudinal strip.

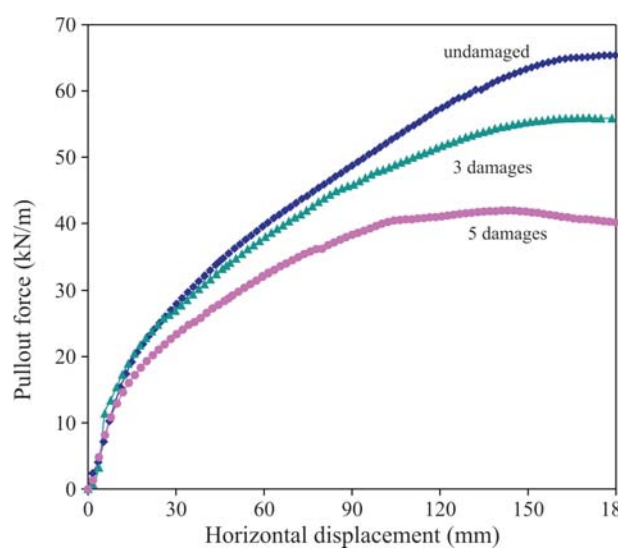


Figure 13 - Pullout tests in sand: damage in geogrid's transverse strip.

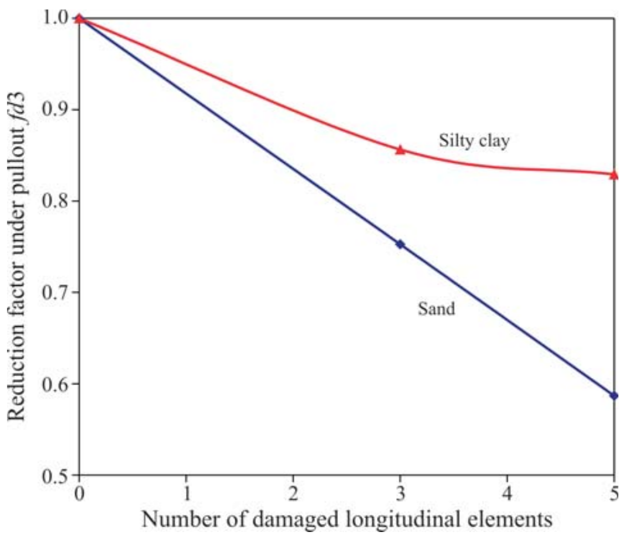


Figure 14 - Susceptibility index for damage of geogrid immersed in sand and in silty clay.

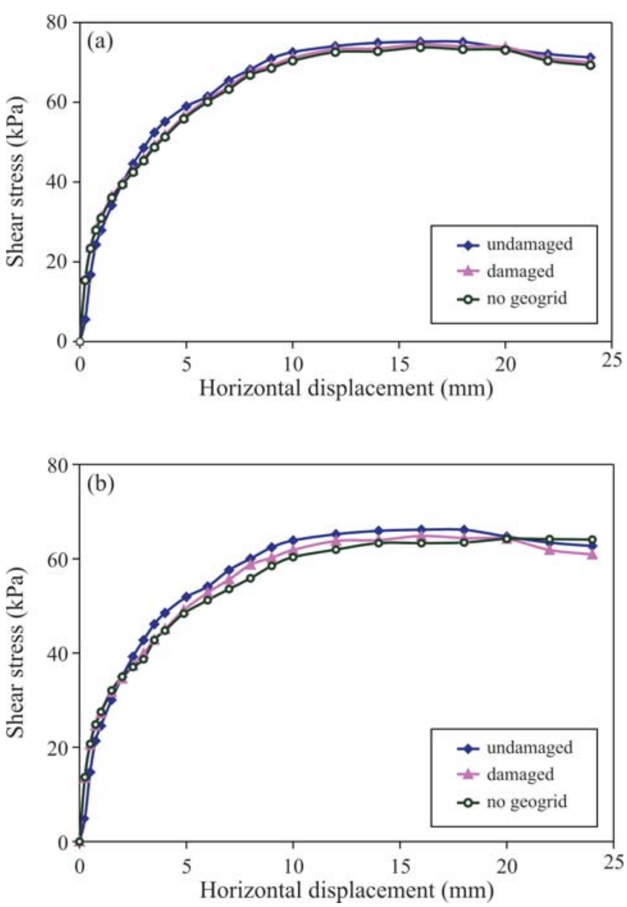


Figure 15 - Direct shear results in artificially damaged geogrid.

silty clay. For performance comparison, direct shear results of soil specimens with no reinforcement are also shown. A confining stress of 100 kPa was applied in all tests.

The loss in strength due to damage is noted to be insignificant. A reduction factor $f_d = f_{d4} = 1.0$ (corresponding to $S = 0$) may be considered representative for both sand and silty clay tests. This observation may be explained with basis on the results previously presented in Fig. 8. Up to a tensile deformation of about 3%, the behavior of intact geogrid is similar to the one with damage in the longitudinal element. In direct shear tests with vertical reinforcement, the geogrid is submitted to traction. Depending on the longitudinal deformation induced by shearing, the mobilized tensile resistance may be not yet influenced by the damage.

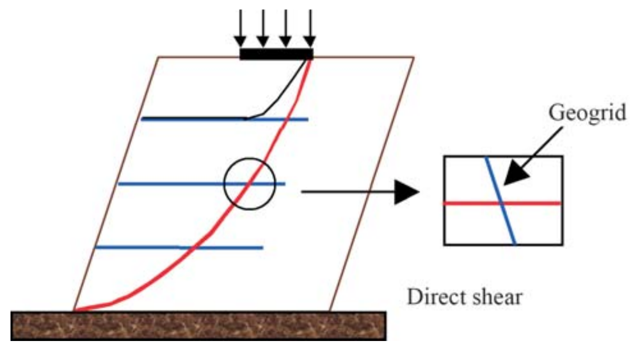


Figure 16 - Field condition simulated by direct shear tests with inclined reinforcement (Palmeira & Milligan, 1989).

It is also noted that geogrids in vertical direction have negligible influence in direct shear results. This explains the insignificant influence of geogrid damage on results of tests, *i.e.*, the presence of the geogrid (with or without damage) has little influence.

These results suggest that, in field situations where the geogrid is nearly perpendicular to the potential failure surface, eventual damage may not compromise the integrity of the reinforced mass. These situations may be found in the upper part of the reinforced fill, as illustrated in Fig. 16.

5. Conclusions

This paper presents an investigation on the influence of mechanical damage on the behavior of geogrids. The experimental program included unconfined tension, pullout and direct shear tests with geogrids in sand and silty clay. Two distinct types of mechanical damage were imposed in the laboratory: natural and artificial damage.

Natural damage was shown to be more relevant when aggressive compaction procedures were imposed to coarse grained soils in contact with the geogrid. In sands, low energy procedures by manual compaction did not result in damaging the geogrid. In silty clay, damage was not significant, even when high energy compaction was applied.

Results of unconfined tension tests in artificially damaged geogrid revealed that rupturing a longitudinal element caused a strength loss of about 22%, corresponding to a reduction factor of 1.27. When a transverse element was ruptured, the strength loss was much less significant.

Under pullout loading, however, transverse elements were shown to contribute significantly to the overall strength, due to its anchoring effect. Therefore, damage in these transverse elements may not be neglected when pull-out conditions prevail in the field.

In direct shear, the results indicated that the relative position of the geogrid relative to the potential failure surface is an important factor. When the geogrid was placed in a nearly perpendicular direction relative to the failure surface, damage in the geogrid was not of concern. This is usually the case of the upper geogrid layers within reinforced fills.

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