Influence of Geogrid Geometrical and Mechanical Properties on the Performance of Reinforced Veneers

Helber N.L. Viana, Ennio M. Palmeira

Abstract. Some types of geosynthetics have been traditionally used as reinforcement in several types of geotechnical projects. They can also be used as reinforcement to increase the stability of cover soils in slopes of waste disposal areas. This paper investigates the influence of some geometrical and mechanical properties of geogrids on the stability of cover soils using a large scale ramp test. Tests were performed with a sand and different combinations of geosynthetics, involving the use of geogrids, a nonwoven geotextile and rough and smooth geomembranes. The elevation of the geogrid in the cover soil was varied in the test programme. The results obtained show a marked influence of the presence of geogrid reinforcement in the cover soil on the stability of the system and on the reduction of tensile forces mobilised in the geomembrane during the test in tests with smooth or rough geomembranes. The beneficial effect of the presence of the geogrid in the cover soil was a function of its geometrical and mechanical properties.

Keywords: geosynthetics, veneers, reinforcement, ramp test, cove soil stability.

1. Introduction

The stability of veneers on slopes of waste disposal areas or in protective works against slope erosion has to be carefully evaluated to avoid failures that may cause significant cost and time to repair. Works in the literature (Dwyer *et al.* 2002, Gross *et al.* 2002, Blight 2007) have reported failures of cover soils of slopes of waste disposal areas or of final covers of landfills due to low adherence between soils and geosynthetics or due to tensile failure of the geosynthetic layer caused by excessive mobilization of tensile forces. Figures 1(a) and (b) show some examples of such failures. The occurrence of these types of failure mechanisms can be avoided or minimised with the use of geosynthetic reinforcement in the cover soil (Palmeira & Viana 2003, Palmeira *et al.* 2008).

Several authors have reported the use of geogrid layers installed directly on the geomembrane to increase the stability of cover soils and to reduce tensile forces mobilised in geomembranes (Chouery-Curtis & Butchko 1991, Quinn & Chandler 1991, Chiado & Walker 1993, Fox 1993, Wilson-Fahmy & Koerner 1993, Baltz *et al.* 1995, Sperling & Jones 1995, Palmeira *et al.* 2002, Palmeira & Viana 2003, for instance). Palmeira & Viana (2003) performed large scale ramp tests to study the behaviour of reinforced cover soils where the reinforcement layer was installed parallel to the slope surface but at varying elevations above the geomembrane. Palmeira *et al.* (2008) reports the use of horizontal reinforcement layers to increase the stability of cover soils in landfills. The arrangement with the reinforcement installed parallel to the slope is more practical than the use of horizontal reinforcement layers, but stronger and stiffer reinforcements are required, particularly for long slopes. In either case, the presence of the reinforcement increases the stability conditions of the cover soil and reduces its deformability, as well as the tensile loads mobilised in the geomembrane (Palmeira & Viana 2003, Palmeira 2009).

Direct shear tests, pull-out tests and ramp or inclined plane tests are usual testing techniques to evaluate the adherence between soils and geosynthetics. The advantage of the latter with respect to direct and pull-out tests is that tests under very low normal stresses can be performed, which is consistent with the actual low stress levels at the soil-geosynthetic or geosynthetic-geosynthetic interfaces in slope veneers. The use of conventional direct shear tests under such low stress levels or the extrapolation of results of direct shear tests carried out under higher stress levels can yield to unsafe values of interface strength parameters, as reported by Girard *et al.* (1990), Giroud *et al.* (1990) and Gourc *et al.* (1996), for instance.

Ramp tests to evaluate adherence between different materials have been performed by several researchers (Girard *et al.* 1990, Giroud *et al.* 1990, Koutsourais *et al.* 1991, Girard *et al.* 1994, Gourc *et al.* 1996, Izgin & Wasti 1998, Lalarakotoson *et al.* 1999, Lima Junior 2000, Lopes *et al.* 2001, Mello 2001, Wasti & Özdüzgün 2001, Palmeira *et al.* 2002, Viana 2003, Viana 2007, Aguiar 2003, Palmeira & Viana 2003, Viana 2007, Aguiar 2008). Palmeira *et al.* (2002) report the results of tests on different interfaces using a large scale ramp test device. The advantage of a large ramp apparatus is that the distribution of normal stresses on the interface can be more uniform than that in a smaller apparatus and there is less influence of the boundary conditions on the results obtained.

Helber N.L. Viana, PhD., Ministry of National Integration, Secretariat of Water Infrastructure, SIH, 70067-901, Brasília, DF, Brazil. e-mail: helber@unb.br.
Ennio M. Palmeira, PhD., Professor, University of Brasília, Department of Civil and Environmental Engineering, FT, 70910-900 Brasília, DF, Brazil. e-mail: palmeira@unb.br.

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(a) Dwyer *et al.* (2002).

(b) Gross *et al.* (2002).

Figure 1 - Cover soil failures in landfills. (a) Dwyer *et al.* (2002). (b) Gross *et al.* (2002).

This paper examines the influence of reinforcement in cover soils using a large ramp test device. The study focus on the influence of geometrical and mechanical properties of geogrid reinforcement on the performance of reinforced cover soils.

2. Experimentals

2.1. Equipment used in the tests

A large ramp test apparatus was used in the experimental programme. Figures 2 and 3 show the apparatus and the test arrangement (Palmeira & Viana 2003). Boxes with varying heights were used to confine the soil and the box heights could be chosen according to the soil sample height and reinforcement elevation (y in Fig. 3). The internal dimensions of the boxes were 1920 mm (length) and 470 mm (width) and the total height of the soil sample (H in Fig. 3) in the present series of tests was equal to 200 mm. The geosynthetic layers tested were fixed to the ramp by clamps connected to load cells for the measurement of mobilised tensile loads at the geosynthetic end during testing (Fig. 3). The roughness of the surface of the ramp in the present series of tests was reduced using double layers of plastic films and oil, yielding to an interface friction angle between ramp surface and the smooth HDPE geomembrane used in the tests of approximately 6°. Displacement transducers allowed the measurement of relative displacements between the soil sample and the ramp. The methodology of the test consisted on increasing the inclination of the ramp to the horizontal direction (α, in Fig. 3) until sliding of the top soil block occurred.

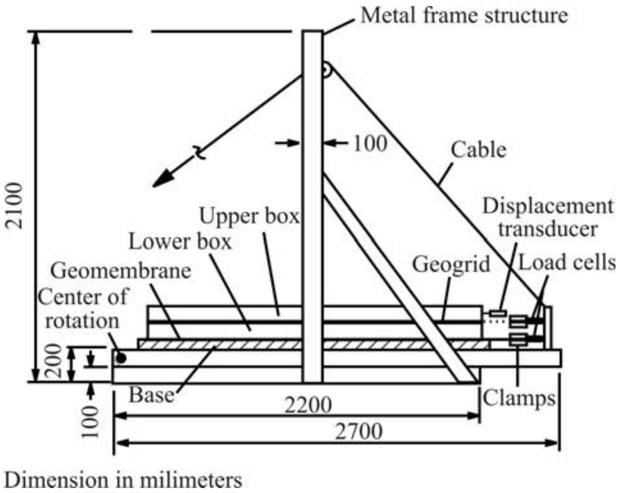


Figure 2 - Large ramp test apparatus.

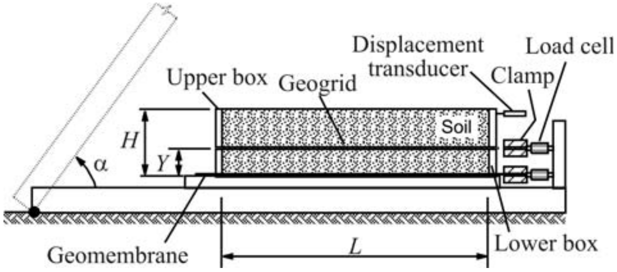


Figure 3 - Test setup.

The values of the elevation (y) of the reinforcement layer inside the cover soil used were 0, 0.05 m, 0.10 m and 0.15 m. Tests with reinforcement at varying elevations and a nonwoven geotextile layer directly on the geomembrane were also carried out. A geotextile layer on the geomembrane is a common measure to minimise the risk of mechanical damage to the geomembrane or to reduce the shear loads transferred to the geomembrane by the cover soil.

2.2. Materials tested

The soil used in the tests was a uniform coarse sand, with particle diameters varying between 0.6 mm and 2 mm.

Table 1 summarises the main properties of this sand. The sand was compacted in the testing box in 5 cm thick layers by tamping using a compaction energy per unit volume of soil of 1.56 kN.m/m^3, to reach a target relative density of 57%.

Table 1 - Properties of the sand used in the tests.

Property(1)	
D_{10} (mm)	0.63
D_{60} (mm)	1.00
CU	1.61
G_s	2.57
ϕ (degrees)	37(2)

Notes: (1) D_{10} = diameter for which 10% of the soil in mass have particles smaller than that diameter, D_{60} = diameter for which 60% of the soil in mass have particles smaller than that diameter, CU = soil coefficient of uniformity, G_s = soil particle density and ϕ = soil friction angle; (2) Friction angle obtained from tests on the sand using the ramp test equipment under similar stress level as that in the ramp tests with geosynthetics.

The geosynthetic materials used in the tests comprised two geomembranes, a nonwoven geotextile and several geogrids. Table 2 presents the main properties of the geosynthetics used. Geomembrane GMS is a smooth HDPE geomembrane, whereas geomembranes GMR-A and GMR-B are rough HDPE geomembranes, respectively, with different roughness conditions. Figures 4(a) and (b) show the surface characteristics of these geomembranes. The roughness of the surface of geomembrane GMR-A is not uniform and consists of a succession of rough rib-like bumps, which locally interacts with soil by bearing, on a rather smooth surface. The roughness of the geomembrane GMR-B can be considered as uniform and similar to a sandpaper surface. The nonwoven geotextile (code GTNW) was a needle-punched product, made of polypropylene, with a mass per unit area of 200 g/m^2. The several geogrid geometries tested were obtained by cutting longitudinal or transverse members of two reference geogrids (GG-A and GG-H, Fig. 5), made of polyester, to obtain the geometrical patterns of the other grids (GG-B to GG-G and GG-I to GG-O). By cutting transverse and/or longitudinal members of such grids, one can vary the grid solid surface per unit area, the bearing load capacity of the grid and/or its tensile strength and stiffness. The removal of grid trans-

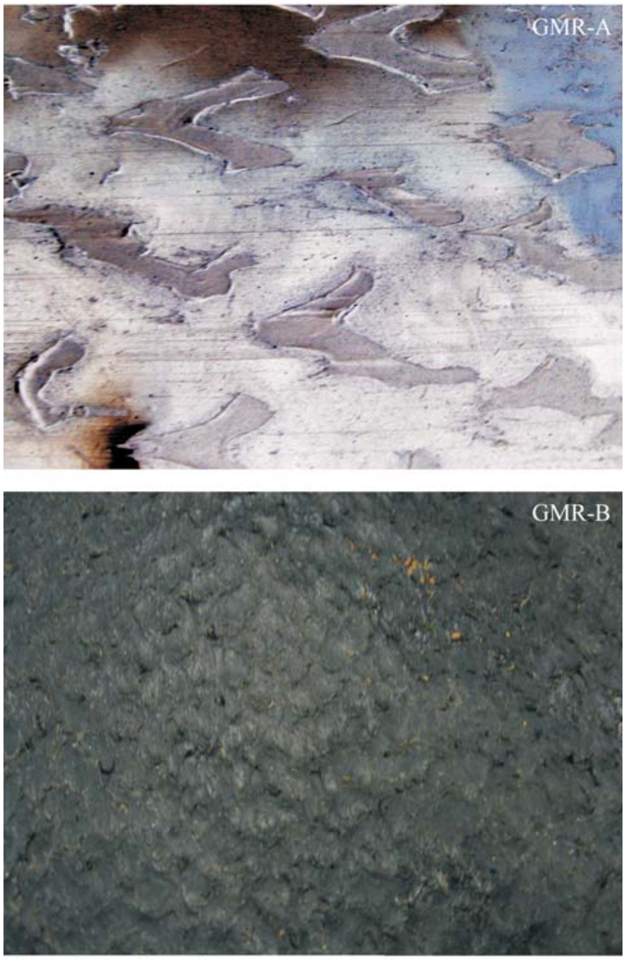
Table 2 - Geosynthetics tested.

Geosynthetic	Code	M_A(2) (g/m^2)	t_G(3) (mm)	T_{max}(4) (kN/m)	ε_{max}(5) (%)	J(6) (kN/m)	N(7)	Aperture(8) (mm)
Geotextile (PP)(1)	GTNW	200	2.2	12	60	22	—	—
Geomembranes (HDPE)(1)	GMS	950	1.0	20/33(9)	12/700(9)	260	—	—
	GMR-A	950	1.0	20/33(9)	12/700(9)	260	—	—
	GMR-B	940	2.0	29/21(9)	12/100(9)	300	—	—
Geogrids (PET)(1)	GG-A	250	1.1	20	12.5	200	96	20 x 20
	GG-B	233	1.1	10	12.5	100	96	20 x 40
	GG-C	227	1.1	5	12.5	50	96	20 x 80
	GG-D	168	1.1	2.5	12.5	25	96	20 x 160
	GG-E	228	1.1	20	12.5	200	48	40 x 20
	GG-F	213	1.1	20	12.5	200	24	80 x 20
	GG-G	205	1.1	20	12.5	200	12	160 x 20
	GG-H	760	1.6	200	12.0	1670	10	200 x 40
	GG-I	739	1.6	100	12.0	835	10	200 x 80
	GG-J	719	1.6	50	12.0	417.5	10	200 x 160
	GG-L	699	1.6	25	12.0	208.75	10	200 x 320
	GG-M	748	1.6	200	12.0	1670	5	400 x 40
	GG-N	737	1.6	200	12.0	1670	2	800 x 40
	GG-O	726	1.6	200	12.0	1670	1	1600 x 40

Notes: (1) PP = polypropylene, HDPE = high density polyethylene, PET = polyester; (2) M_A = mass per unit area; (3) t_G = thickness; (4) T_{max} = tensile strength from wide strip tensile tests; (5) ε_{max} = maximum tensile strain from wide strip tensile tests; (6) J = tensile stiffness from wide strip tensile tests; (7) N = number of grid transverse members; (8) Value on the left is parallel to the grid longitudinal member and value on the right is parallel to the transverse members; (9) Value on the left is at yielding and on the right at rupture.

verse members will also influence the amount of interference among these members (Palmeira and Milligan 1989, Palmeira 2004 and 2009).

(a) Smooth geomembrane surface.



(b) Surfaces of rough geomembranes.

Figure 4 - Surface characteristics of the geomembranes tested. (a) Smooth geomembrane surface. (b) Surfaces of rough geomembranes.

3. Results Obtained

3.1. Tests with geomembranes only

The results obtained for ramp tests with the geomembranes only are presented in Figs. 6(a) and (b). Sliding of the cover soil on the geomembrane occurred for ramp inclinations of 26° for geomembrane GMS, 29° for geomembrane GMR-B and 31° for geomembrane GMR-A (Fig. 6a).

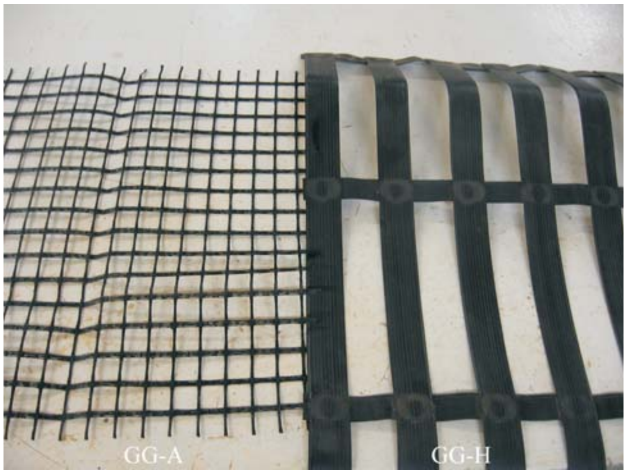


Figure 5 - Reference grids GG-A and GG-H.

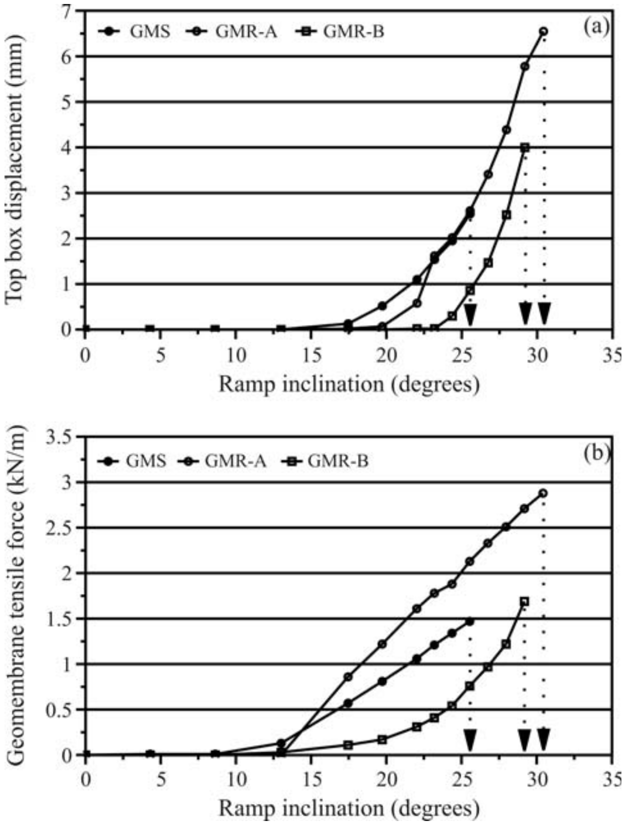


Figure 6 - Ramp tests on geomembranes. (a) Top box displacement *vs.* ramp inclination. (b) Geomembrane tensile force *vs.* ramp inclination.

These results show the influence of roughness on the adherence between cover soil and geomembrane. It is interesting to note that the development of box displacements for tests with geomembranes GMS and GMR-A was similar up to box displacements of 26°(failure of the sand-GMS interface). To some extent, this can be explained by the characteristics of the surface of geomembrane GMR-A (discrete bumps on a smooth surface), as described before. Thus, sliding must have occurred first in the smooth parts of the geomembrane followed by bearing failure at the bumps, the latter being responsible for the increase of 5° on ramp inclination at failure in comparison with the result obtained for geomembrane GMS.

The mobilisation of tensile forces in the geomembranes during the test are shown in Fig. 6(b). The pattern of tensile force during ramp inclination was very distinct among the geomembranes. One should bear in mind that the mobilisation of tensile forces in the geomembrane also depends on the adherence between geomembrane and ramp surface. The progressive failure mechanism developed in this type of test (Palmeira *et al.* 2002, Fox & Kim 2008 and Palmeira 2009) also influences the pattern of force mobilisation in the geomembrane.

3.2. Influence of the presence of geogrid and geotextile on reinforced veneer behaviour

3.2.1. Tests with the smooth geomembrane

Figures 7(a) and (b) show the results obtained for tests with the smooth geomembrane (GMS) and the reference geogrids GG-A and GG-H positioned at different elevations regarding top box displacements *vs.* ramp inclination. It can be seen that for both geogrids a marked increase on the ramp inclination at failure was obtained with respect to the test on the unreinforced cover soil. The presence of the geogrid causes failure to take place along the soil-geogrid interface, rather than along the soil-geomembrane interface. Under these circumstances, the ramp inclination at failure was closer to the sand friction angle (37°). The results also show that the systems with the geogrid directly on the geomembrane (y = 0) presented a very distinct behaviour in comparison to the cases where the geogrid was located some distance above the geomembrane. The elevation of the geogrid influenced the development of top box displacement with largest displacements for y = 0. The elevation of the geogrid affected less the ramp inclination at failure, except for the case with y = 0 and particularly for geogrid GG-H, where the ramp inclination at failure was significantly smaller than those observed for y > 0. It is also interesting to note that for y > 0 the presence of the geogrid in the cover soil yielded values of ramp inclination at failure in tests with the smooth geomembrane greater that those obtained for the tests with the rough geomembranes GMR-A and GMR-B only (Figs. 6a and b). Therefore, for the materials tested and test conditions the presence of the geogrid compensated for the smoothness of geomembrane GMS, regarding ramp inclination at failure.

The presence of a geotextile layer on the geomembrane reduced even further the displacements of the top box during ramp inclination, as seen in Fig. 8(a) for tests with y = 0.1 m. The presence of the geotextile also slightly increased the ramp inclination at failure. The mobilised tensile forces in the smooth geomembrane GM-S were also reduced due to the presence of the geotextile, as shown in Fig. 8(b). Independent on the geogrid considered, a significant reduction on forces in the geomembrane can be noted, with the test with GG-H presenting slightly less geomembrane forces than the test with GG-A. However, the presence of the geotextile layer on the geomembrane had a more significant effect on the test with geogrid GG-H.

3.2.2. Tests with rough geomembranes

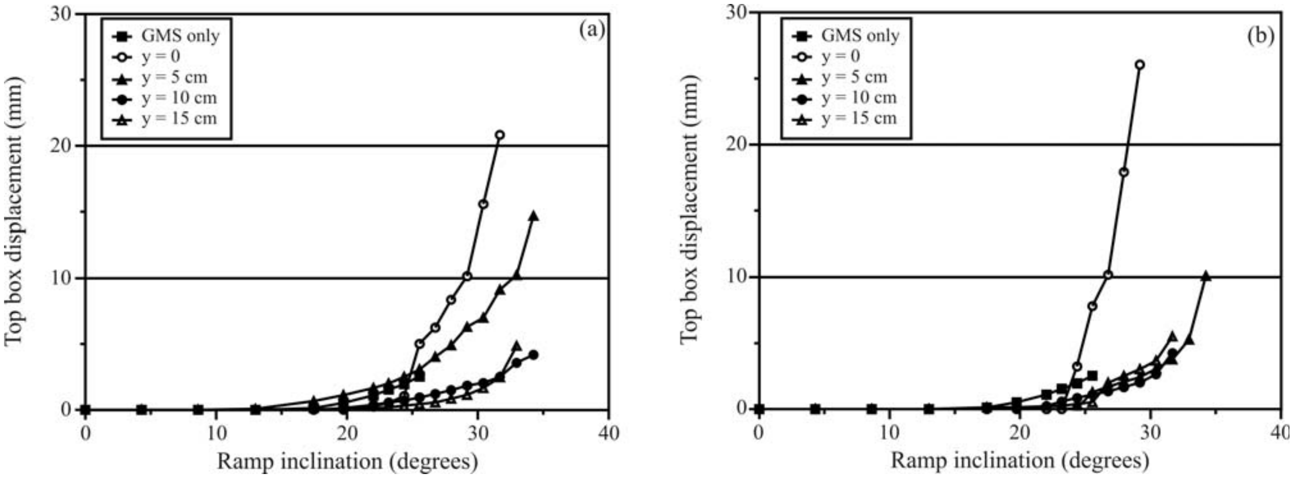


Figure 7 - Results of tests on cover soils reinforced with geogrids at varying elevations – geomembrane GMS. (a) Tests with geogrid GG-A. (b) Tests with geogrid GG-H.

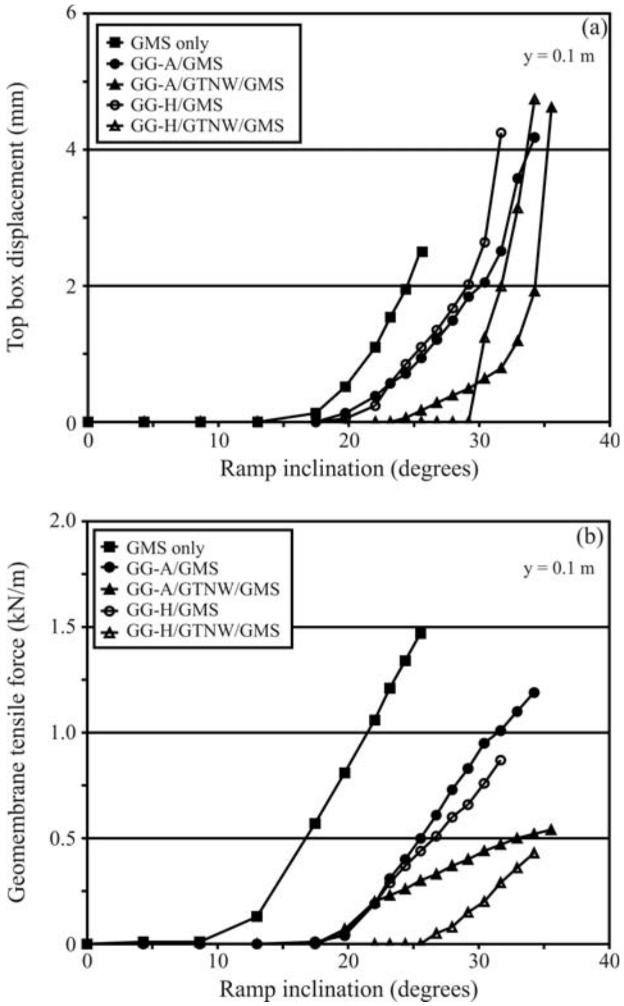


Figure 8 - Influence of the presence of a geotextile on the smooth geomembrane. (a) Top box displacement *vs.* ramp inclination. (b) Geomembrane tensile force *vs.* ramp inclination.

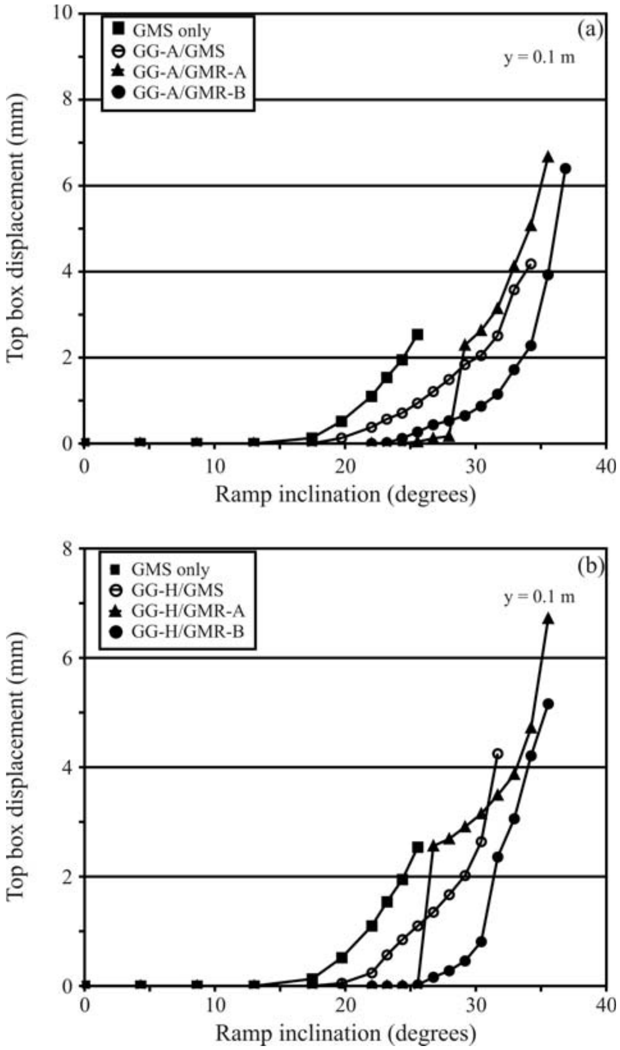


Figure 9 - Tests with rough geomembranes GMR-A and GMR-B. (a) Tests with geogrid GG-A. (b) Tests with geogrid GG-H.

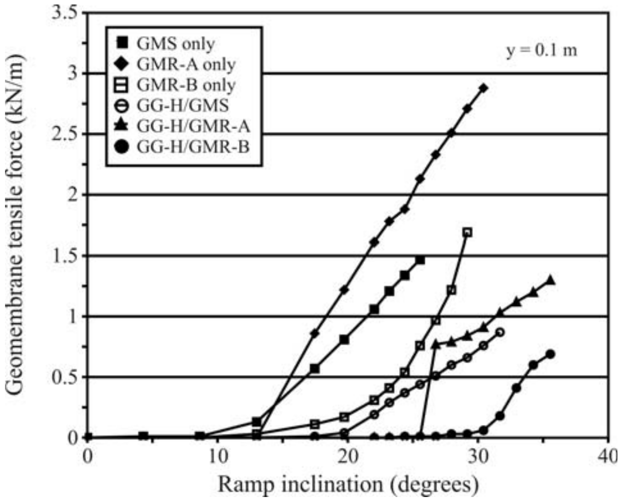


Figure 10 - Geomembrane tensile forces in tests with geogrid GG-H.

Results of top box displacement *vs.* ramp inclination obtained in tests on unreinforced and reinforced (y = 0.1 m) cover soils with rough geomembranes GMR-A and GMR-B and geogrids GG-A and GG-H are presented in Figs. 9(a) and (b). Again, the presence of the geogrid in the cover soil caused a marked increase on the ramp inclination at failure. Interesting features are the sudden increase of top box displacements for the tests with geomembrane GMR-A at ramp inclinations of 28 degrees for geogrid GG-A and 26 degrees for geogrid GG-H. This occurrence was more intense in the test with geogrid GG-H and influenced the variation of mobilised tensile load in the geomembrane with ramp inclination, as shown in Fig. 10, although the forces in the geomembranes in the tests with grid reinforcement in the cover soil remained considerably lower than those in the tests without reinforcement (Fig. 10).

The sudden increases of top box displacement and geomembrane forces mentioned above are certainly associated with the characteristics of the surface of geomembrane

GMR-A, commented before. This type of behaviour was neither observed in the tests with the uniformly roughened geomembrane GMR-B nor in the tests with GMR-A only (Fig. 6). It is interesting also to note that the sudden increase on top box displacement and geomembrane tensile force occurred at ramp inclinations (26° and 28° for geogrids GG-H and GGA, respectively) close or slightly greater than the value at failure for the test with the smooth geomembrane. It is likely that sliding of the sand on the smoother parts of the surface of geomembrane GMR-A will increase the passive resistance at the rib-like bumps and cause dilation at the sand-geomembrane interface. The presence of the geogrid in the cover soil will inhibit dilation and increase confinement on the geomembrane. The results obtained show that the presence of the geogrid reinforcement caused a complex interaction mechanism with the rough geomembrane GMR-A. As it was observed in the tests with the smooth geomembrane, the presence of the geogrid also increased markedly the ramp inclination at failure and reduced the tensile loads mobilised in the rough geomembranes.

Figures 11 and 12 show the influence of the presence of a nonwoven geotextile layer on the rough geomembranes for tests with geogrids GG-A and GG-H, respectively. The presence of the geotextile layer did not influence significantly the development of top box displacement during the tests with geomembrane GMR-B (Figs. 11a and 12a). More important influence on box displacement was observed for the test with geomembrane GMR-A and geogrid GG-H (Fig. 12a). In this case the presence of the geotextile attenuated the sudden increase in top box displacements observed for the tests with geogrid in the cover soil only. The presence of the geotextile further reduced the tensile force mobilised in the geomembranes for both grids (Figs. 11b and 12b) and attenuated the sudden increase in geomembrane force observed in tests with the geogrids only, particularly for the case of geogrid GG-H (Fig. 12b).

Figures 13(a) to (c) show the reductions on tensile force in the geomembrane in tests with geogrid and/or geotextile, with respect to the force mobilised in the geomembrane in the tests without geogrid and geotextile, when sliding of the cover soil occurred (y = 0.1 m). Reductions of forces over 50% can be observed in all cases, with greater reductions when geogrid in the cover soil and geotextile on the geomembrane were used. This was particularly so for tests with geomembrane GMR-B (Fig. 13c). These results show that the benefit brought by the presence of the geotextile layer on the geomembrane is twofold. First, it

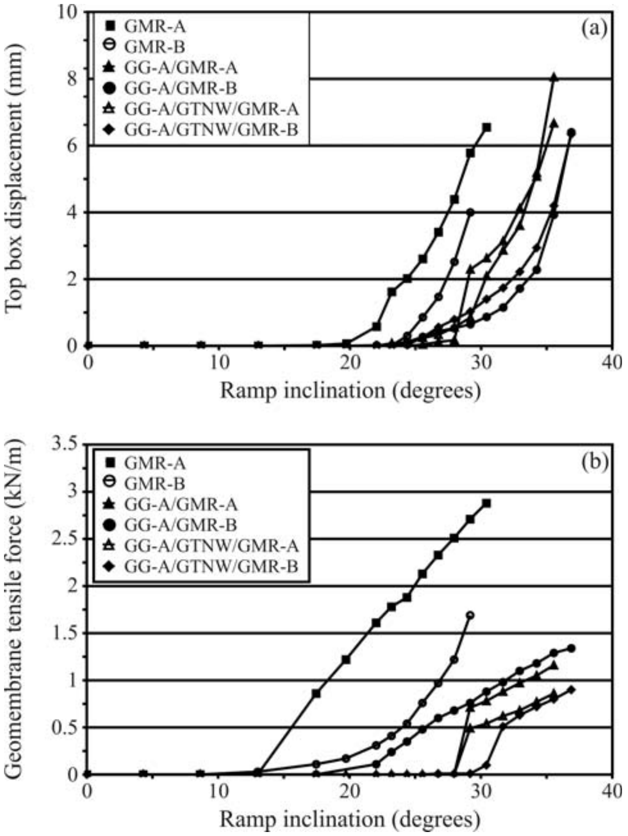


Figure 11 - Influence of the presence of geotextile in tests with rough geomembranes – Tests with and without geogrid GG-A. (a) Top box displacements. (b) Mobilised tensile forces in the geomembrane.

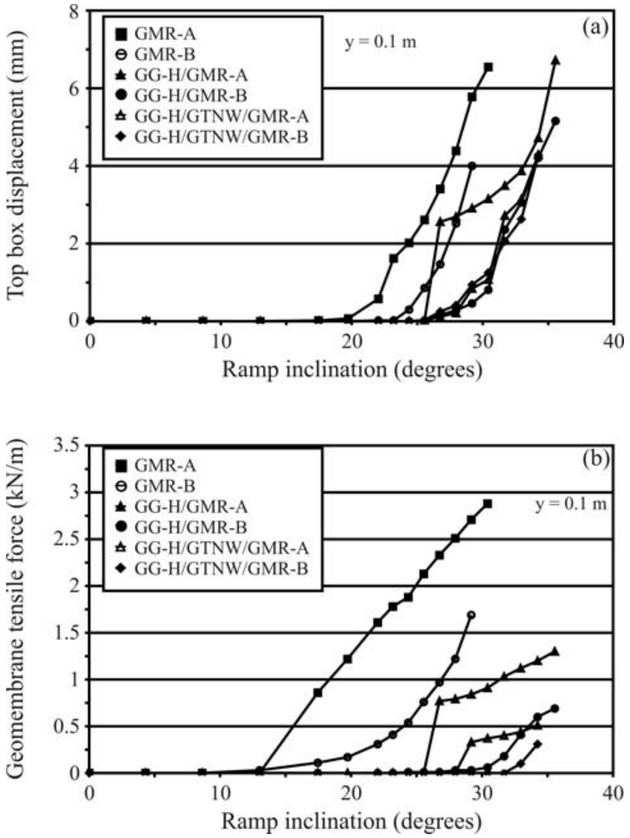


Figure 12 - Influence of the presence of geotextile on top box displacements in tests with rough geomembranes – Tests with geogrid GG-H. (a) Top box displacements. (b) Mobilised tensile forces in the geomembrane.

reduces the possibility of mechanical damage of the geomembrane and second it may reduce even further the tensile force mobilised in the geomembrane.

3.3. Influence of reducing the number of grid longitudinal members

By removing grid longitudinal members, one can reduce the geogrid tensile stiffness (J). The removal of such members not only reduces grid stiffness but also the skin friction between grid and soil and changes grid geometry, increasing aperture size and reducing bending stiffness of transverse members. Palmeira & Viana (2003) presented a preliminary study on the effects of the reduction of longitudinal and transverse members of geogrids on the stability of cover systems, but on a limited basis in comparison to the present study, regarding the variety of geosynthetics products and characteristics investigated. Figures 14(a) and (b) show the effects of altering geogrid aperture size (reductions of up to 80% on the reference grid GG-A original stiffness, J_o) on top box displacements and geomembrane mobilised tensile forces (for y = 0.1 m). As the number of longitudinal members removed increases, so does the displacement of the top box close to failure (Fig. 14a). The ramp inclination at failure was less influenced by the removal of the grid longitudinal members. With the exception of the test with grid GG-D ($J = 0.125J_o$), whose results were close to those of the unreinforced test, the development of top box displacement up to a value of ramp inclination of 32° were similar for grids GG-A to GG-C. The influence of the removal of grid longitudinal members was more significant on the tensile force in the geomembrane (Fig. 14b), but with little difference among results obtained for grids GG-B to GG-D. As the grid aperture increases, greater loads are expected to be transferred to the geomembrane.

Figures 14(a) and (b) also present the result of tests with geogrid GG-C ($J = 0.25J_o$) and the nonwoven geotextile on the geomembrane (test code GG-C/GTNW in Figs. 14a and b). Again these results show a beneficial effect of the geotextile presence in as far as that the test with the combination GG-C/GTNW presented results very close

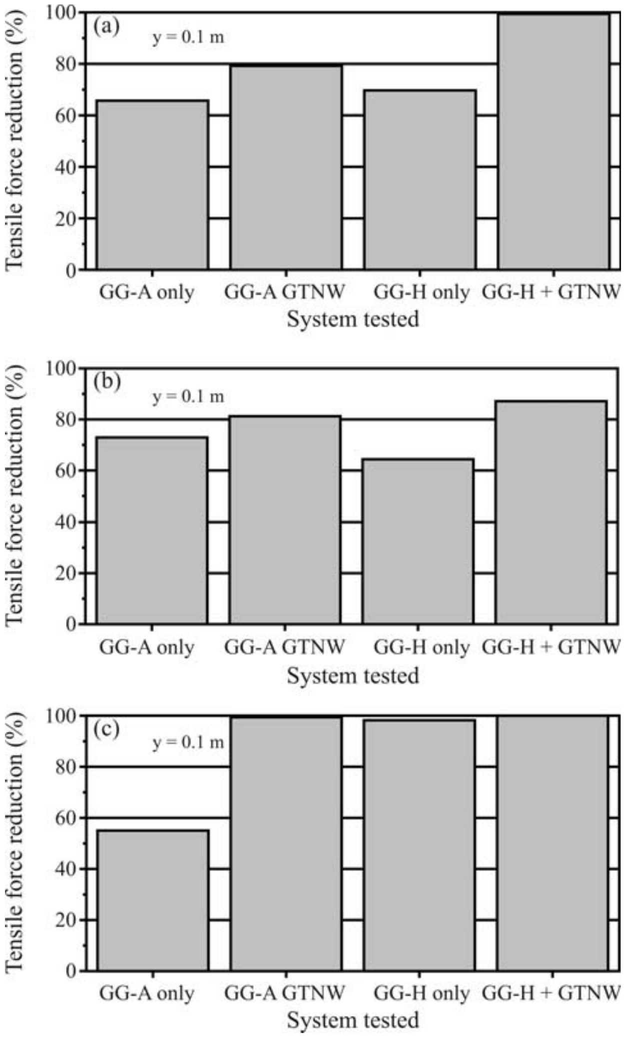


Figure 13 - Reductions on geomembrane tensile force for the ramp inclination of the unreinforced system at failure. (a) Tests with smooth geomembrane GMS. (b) Tests with rough geomembrane GMR-A. (c) Tests with rough geomembrane GMR-H.

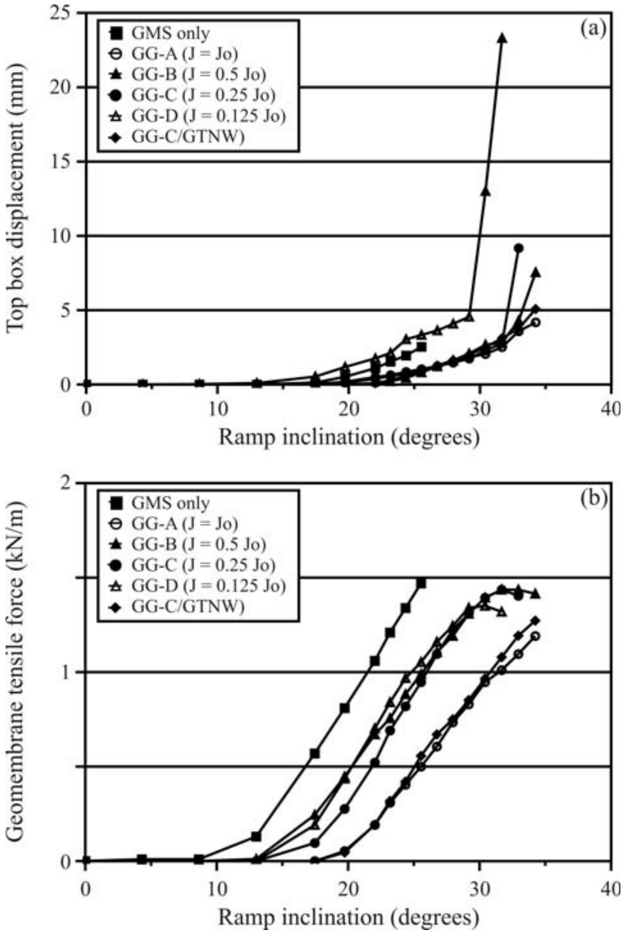


Figure 14 - Influence of the reduction of grid longitudinal members – Geogrid GG-A. (a) Top box displacement *vs.* ramp inclination. (b) Mobilised tensile forces in the geomembrane.

to those obtained in the test with the reference geogrid GG-A. Therefore, the presence of the geotextile compensated for the reduction of geogrid tensile stiffness and increase of geogrid open area.

The effects of the removal of longitudinal members of grid GG-H are shown in Figs. 15(a) and (b) (y = 0.1 m – geogrids GG-I to GG-L), where in this case J_o is the tensile stiffness of the reference grid GG-H. Again, the ramp inclination at failure was not much affected by the changes in grid geometry, but the influence of these changes was slightly more clearly noticed for the grids resulting from the removal of members of grid GG-H than for those resulting from the removal of members of grid GG-A. Again, the combination of a less stiff and more opened geogrid (geogrid GG-J, $J = 0.25J_o$) and geotextile on the geomembrane (test code GG-J/GTNW in Figs. 15a and b) improved the performance of the system, with respect to the test with the geogrid only.

3.4. Influence of reducing the number of grid transverse members

The removal of grid transverse members reduces the amount of soil-grid interaction by bearing as well as skin friction between soil and geogrid. The influence of reducing the number (N) of grid bearing members was assessed by carefully cutting transverse members from the original reference grids GG-A and GG-H, yielding to grids (GG-E to GG-G and GG-M to GG-O, respectively – Table 2) with up to eight times less transverse members than the reference grids. In this series of tests, the elevation of the grid layer was also kept constant and equal to 0.1 m.

Figures 16(a) and (b) show top box displacements and mobilised tensile loads in the geomembrane *vs.* ramp

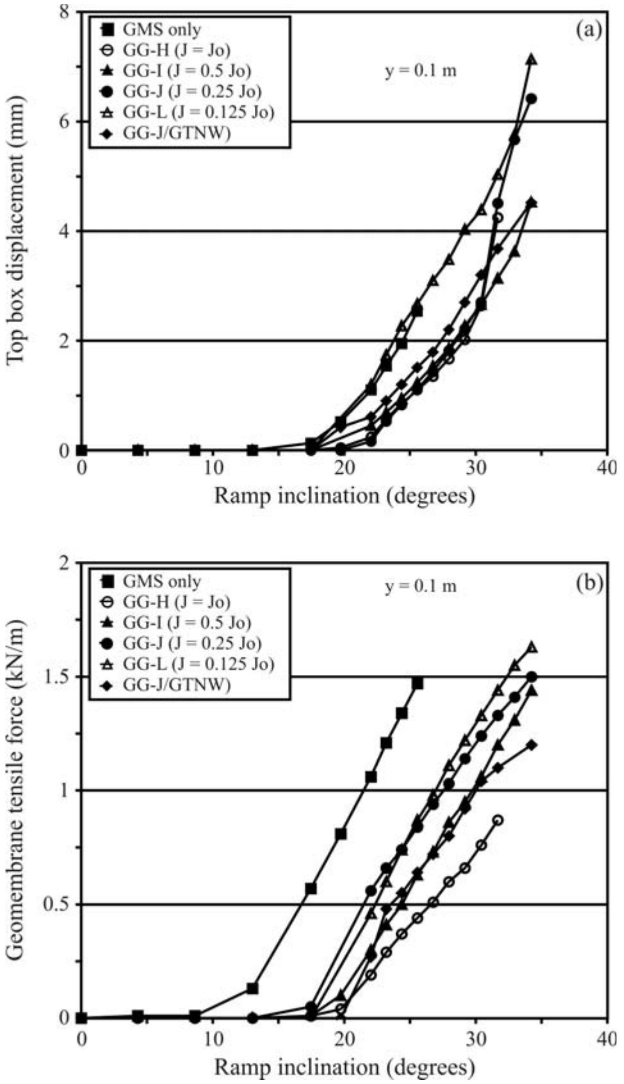


Figure 15 - Influence of the reduction of grid longitudinal members – Geogrid GG-H. (a) Top box displacement *vs.* ramp inclination. (b) Mobilised tensile forces in the geomembrane.

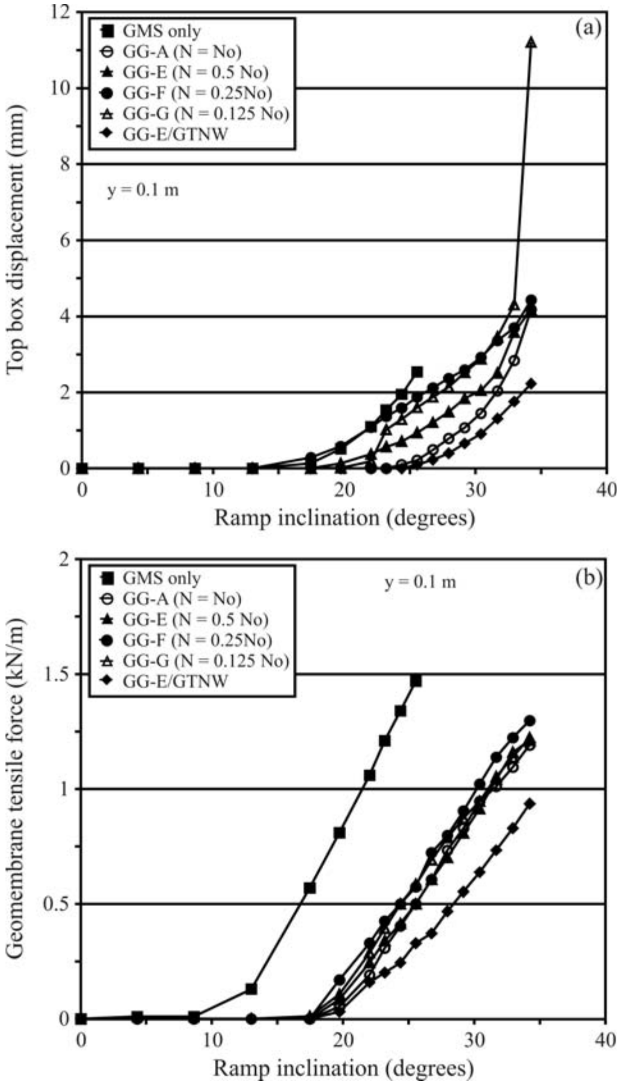


Figure 16 - Influence of the reduction of grid transverse members – Geogrid GG-A. (a) Top box displacement *vs.* ramp inclination. (b) Mobilised tensile forces in the geomembrane.

inclinations for tests with geomembrane GM-S and geogrids GG-E to GG-G, produced by cutting transverse members from the reference geogrid GG-A, for which the number of transverse members is equal to N_o in Figs. 16(a) and (b). It can be noted that the deformability of the system increases with the reduction of the number (N) of transverse members (Fig. 16a). The ramp inclination at failure was not affected by the reduction of transverse members. Failure occurs along the upper interface between soil and geogrid, and the results suggest that the reduction of skin friction between grid surface and soil caused by the removal of transverse members was not significant. The same applies to the mobilised tensile force in the geomembrane, as shown in Fig. 16(b). For the range of values of N tested, the grid was still capable of carrying a considerable amount of load that otherwise would be transferred to the geomembrane. The combination of geogrid GG-E ($N = 0.5N_o$) and geotextile on the geomembrane (test code GG-E/GTNW in Figs. 16a and b) yielded to the best performance in terms of top box displacements and geomembrane tensile forces.

Figures 17(a) and (b) present the influence of the number of transverse members in tests with geogrids (GG-I to GG-L) formed by the reduction of the number (N) of transverse members of the reference grid GG-H (for which $N = N_o$). In this series of tests geomembrane GM-S was used and the grid elevation was equal to 0.1 m. The removal of transverse members increased a little the ramp inclination at failure observed for grid GG-H and had a marked effect on the deformability of the system (Fig. 17a). This was due to the fact that the reduction of the number of transverse members increased the soil to soil contact area (less geogrid solid surface – greater grid apertures). The smaller the number of grid transverse members the smaller the top box displacements at failure. However, less transverse members increased the load transferred to the geomembrane, as can be seen in Fig. 17(b). The removal of transverse members of geogrid GG-H (Fig. 17b) was more influential to geomembrane mobilised tensile loads than the removal of transverse members of geogrid GG-A (Fig. 16b). The smaller the number of transverse members the smaller the ramp inclination for which the geomembrane started to be tensioned and the greater the tensile load mobilised in the geomembrane for a given ramp inclination. The combination of geogrid GG-M ($N = 0.5N_o$) and geotextile on the geomembrane was also beneficial to the reduction of tensile forces in the geomembrane (Fig. 17b), but less influential on the top box displacements (Fig. 17a).

4. Conclusions

This paper presented a study on the influence of the presence of geogrid in the cover soil on the stability of veneers using the ramp test. The main conclusions obtained are summarised as follows.

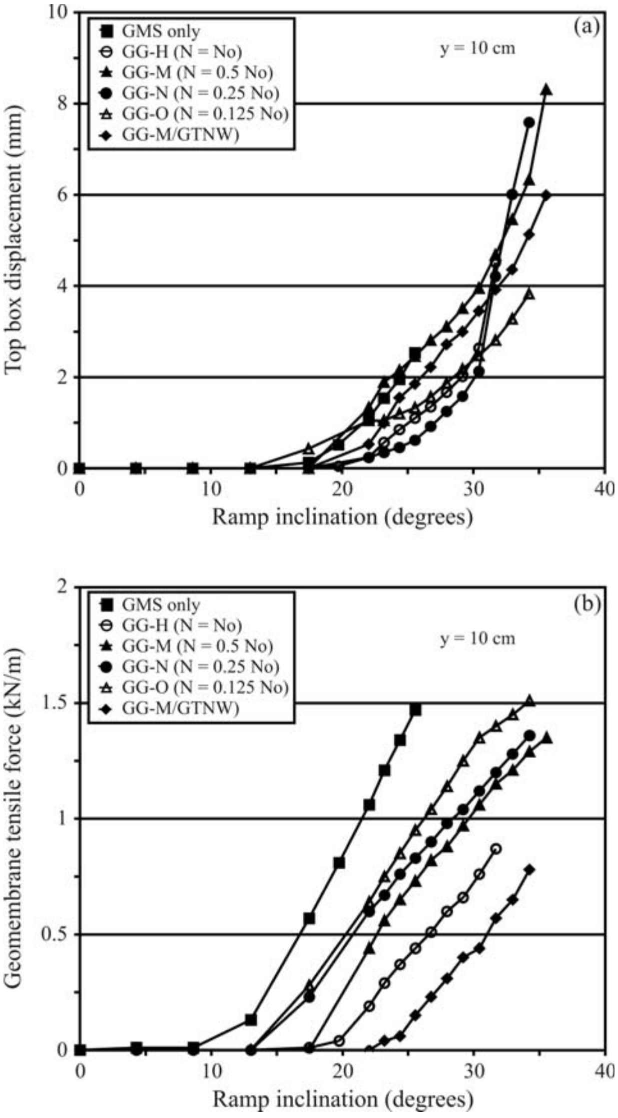


Figure 17 - Influence of the reduction of grid transverse members – Geogrid GG-H. (a) Top box displacement *vs.* ramp inclination. (b) Mobilised tensile forces in the geomembrane.

- The ramp test proved to be a suitable experimental technique for the investigation of soil-geosynthetic interaction under low stress levels, which are typical in cover soils of landfills and waste disposal areas.
- The presence of a geogrid layer in the cover soil increased the ramp inclination at failure and reduced significantly the tensile forces mobilised in the geomembrane. This was observed for both smooth and rough geomembranes.
- The type of roughness of the geomembrane influenced the ramp inclination at failure, development of displacements of the top box and development of tensile forces in the geomembrane.
- The variation of grid geometrical characteristics complicates the interpretation of test results, as the variation of the number of grid members (transverse or longitu-

dinal) also causes variations of grid open area (reduction of soil-geogrid skin friction) and of interference among grid transverse members. These factors can yield to complex modes of interaction among the different materials present in the veneer (soil, grid, geotextile and geomembrane). In general, for the materials and test conditions of the present study, the reduction of the number of grid longitudinal or transverse members increased the deformability of the system and the tensile load mobilised in the geomembrane but had negligible influence on the ramp inclination at failure.

- The presence of a geotextile layer on the geomembrane, besides protecting the latter against mechanical damages, can increase the stability conditions of the system a bit further and reduces the forces transferred to the geomembrane.
- It should be pointed out that the level of contributions due to the presence of geogrid in the cover soil and geotextile on the geomembrane observed in the tests, although encouraging, should be viewed with due care because of the limitations of the testing procedure used, boundary conditions and development of progressive failure mechanisms, for instance. Despite a large scale equipment having been used, the dimensions of the problem in the field are larger and other factors that may play important roles to the stability of actual veneers were not considered in this work. Nevertheless, the results obtained suggest important contributions of geogrid reinforcement to the stability of veneers.

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