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LARGE SCALE RAMP TESTS FOR THE STUDY OF SOIL-GEOSYNTHETIC INTERACTION IN SLOPES OF WASTE DISPOSAL AREAS

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ABSTRACT: The evaluation of soil-reinforcement interaction is of utmost importance in reinforced soil works. The same applies to slopes of waste disposal areas, where single or multiple layers of soils and/or geosynthetics are installed to work as barriers, reinforcement, drains and/or filters. One of the failure mechanisms in these slopes is the sliding of the cover soil placed on the geosynthetic layers and its occurrence depends on the slope inclination and on the interface strength parameters of the layers. The presence of the cover soil induces shear stresses on the geosynthetic layers and sufficient bond along these interfaces is required to avoid failure or excessive deformation of the lining system. This work presents an experimental study on the use of a large scale ramp apparatus to evaluate bond resistances between different soil-geosynthetic interfaces and the influence of the presence of geogrid and geotextile layers on the geomembrane as a measure to increase slope stability and reduce tensile loads in geomembranes. The results obtained show the influence of interface strength parameters on the load transference between geosynthetic layers and the benefits of using geogrids and geotextiles on the geomembrane to increase stability and reduce geomembranes loads.

1 INTRODUCTION

The awareness on the need for environmental protection has increased markedly during the last decades. This has lead to increasing strict legislations and requirements with regard to works involving waste disposal. In this context the use of geosynthetics has also been increasing markedly and expanded for applications not envisaged previously. When used as barriers for liquids and gases the design and specification of the geosynthetic products have to consider aspects such as permeability, diffusion, durability, among others, related to that type of application. However, depending on the case, soil-geosynthetic interaction has also to be properly addressed. This is the case of lining systems incorporating geosynthetics in slopes of waste disposal areas. In such cases there will be a direct contact between soils and geosynthetics and sometimes contact between different geosynthetic products, as schematically presented in Figure 1. The stability of the system depends on the adherence between interfaces and geometrical characteristics of the slope.

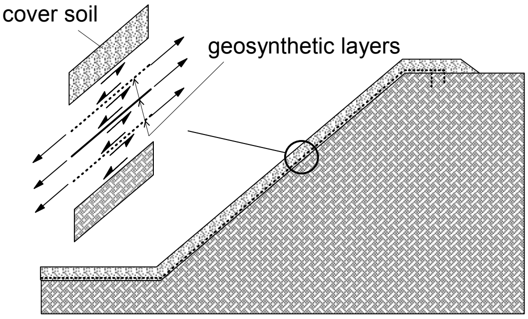


Figure 1 Lining systems in slopes of waste disposal areas.

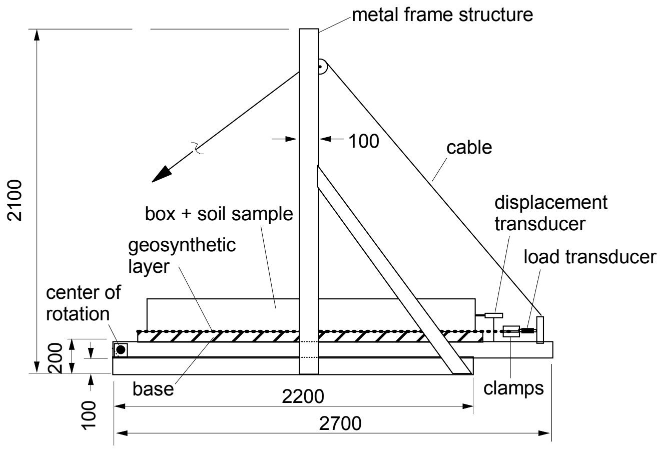
Because of the cover soil on the geosynthetic layer is usually thin, low stress levels act on the interfaces, which raises concerns regarding the utilisation of the conventional direct shear device for the evaluation of bond between soils and geosynthetics or between different geosynthetics under such stress levels. Because of that, several works have addressed the study of such problem with the use of the ramp test (Girard et al. 1990, Giroud et al. 1990, Koutsourais et al. 1991, Girard et al. 1994, Gourc et al. 1996, Izgin and Wasti 1998, Lalarakotoson et al. 1999, Lopes et al. 2001, Wasti and Özdüzgün 2001). Besides, the execution of direct shear tests in standard equipment under low normal stresses may yield to significant errors in the prediction of interface friction angles (Girard et al. 1990, Giroud et al. 1990, Girard et al. 1994, Gourc et al. 1996). The use of the ramp (or inclined plane) apparatus is then more suitable in this case, as its represents more accurately the conditions in the field than the direct shear test, particularly with respect to stress levels on the interfaces.

This paper presents an investigation on the interaction between soils and geosynthetics and between different types of geosynthetics using a large ramp test apparatus.

2 EXPERIMENTALS

2.1 *Apparatus used in the testing programme*

The equipment used in the experiments is shown in Figure 2. It comprises a box 1920 mm long, 250 mm high and 470 mm wide that contains the soil to be placed on the geosynthetic layer. The length of the box was chosen in order to guarantee low influence of normal stress non uniformity on the test results, as discussed in Palmeira et al. (2002). The geosynthetic layer to be tested is clamped to the ramp extremity and up to three geosynthetic layers can be tested simultaneously. Load cells are attached to the clamps for the measurement of the tensile load mobilised at the geosynthetic upper end during the test. It is acknowledged that the ramp test is not a perfect model for the actual conditions found in the field. However, the anchorage of the geosynthetic extremity to the ramp simulates more accurately the conditions found in the field for linings in slopes (Fig. 1), as these materials are anchored close to the slope crest. The large length of the geosynthetic specimen also allows the investigation of other relevant aspects, such as deformation mechanisms and progressive failure at the soil-geosynthetic interface, for instance.



Dimensions in millimeters

Figure 2 Test apparatus

The roughness conditions of the surface of the ramp can be varied for research purposes. Displacement transducers measure the relative displacements between the soil box and the ramp (along the ramp). During the tests the inclination of the ramp with the horizontal is continuously increased up to the slide of the soil block along the interface.

The thickness of the soil layer tested varied between 5 and 20 cm, depending on the subject under investigation, being the soil compacted to target densities by tamping. Concrete blocks with varying heights provided surcharge on top of the soil sample, depending on the normal stress desired on the interface. The surcharge values on top of the soil layer at the beginning of the tests (ramp in the horizontal position) varied between 1.25 and 5.75 kPa. The initial normal stress on the interface was slightly greater than these values due to the contribution of the soil weight.

2.2 *Soils used in the tests*

Two uniform sands and a clayey soil were used in the test programme, whose main characteristics are summarised in Table 1. Soil A is a fine sand (grain sizes between 0.07 and 2 mm) and soil B is a medium to coarse sand (grain sizes between 0.6 to 2 mm). Both sands present angular grain shapes and relative density after sample preparation of 57%. The medium dense state of the sand layer would simulate conditions likely to be found in a slope due to the difficulty of soil compaction under these conditions. The friction angles of these sands varied between 31 and 44^o, depending on the stress level considered, and where obtained under stress levels similar to those acting during the ramp tests. This was achieved by adapting the ramp test equipment to perform shear tests on both sands (Palmeira et al., 2002).

The clayey soil (code Soil C) is a residual soil with 70% in weight passing in the # 200 sieve. The clayey soil sample was compacted with optimum moisture content to its maximum dry density under normal Proctor energy. Additional characteristics of Soil C are also presented in Table 1.

2.3 *Geosynthetics used in the tests*

A large experimental programme was conducted involving different types of geotextiles, geonets, geomembranes and geogrids. This paper summarises results obtained from tests on 5 nonwoven geotextiles, 3 geomembranes and 1 geogrid. The main characteristics of these products are summarised in Table 2. Nonwovens geotextiles codes GNW1 to GNW4 are needle punched geotextiles made of polyester, with different values of mass per unit area, thickness, tensile stiffness, etc but similar surface roughness characteristics and were produced by the same manufacturer. Geotextile GNW5 is a nonwoven product, needle punched, made of polypropylene, but also with similar roughness surface characteristics. The geogrid (code GG1) is a product made of polyester, with square apertures and a tensile stiffness equal to 200 kN/m. The PVC geomembrane GM1 and HDPE geomembranes GM2 and GM3 have very smooth surfaces. Geomembrane GM4 is made of HDPE and has a rough surface to increase its adherence with soil. However, it is not uniformly roughened, but formed by a succession of rough rib-like bumps, which locally interacts with soil by bearing. For the soils used in this research the friction angle between these soils and GM4 was 7 to 12^o greater than the friction angles between the same soils and geomembranes GM1, GM2 and GM3. Geomembrane GM5 is another HDPE rough geomembrane, but with its surface uniformly roughened, like sandpaper.

Table 1 Soil properties

Property$^{(1)}$	Soil A	Soil B	Soil C
Soil Type	Fine sand	Coarse sand	Clay
D_{10} (mm)	0.10	0.63	---
D_{50} (mm)	0.21	0.90	0.002
CU	2.70	1.61	---
% passing #200 sieve	0	0	70
Unit weight (kN/m^3)	14.2	14.5	15.6$^{(2)}$
Density of grains	2.58	2.57	2.70
Relative density (%)	57	57	---
Plasticity Index (%)	---	---	25.2
Optimum moisture content (%)	---	---	24.4
Cohesion (kPa)	0	0	22$^{(4)}$
Friction angle (^{o})	32-44$^{(3)}$	31-40$^{(3)}$	36$^{(4)}$

Notes: (1) D_{10} = particle diameter for which 10% in weight is smaller than that diameter, D_{50} = particle diameter for which 50% in weight is smaller than that diameter, CU = coefficient of uniformity (= D_{60}/D_{10}); (2) Maximum dry unit weight obtained after compaction under Proctor normal energy; (3) Dependent of stress level, range of values for normal stresses between 2 to 7 kPa; (4) Test speed in standard direct shear tests was the same average test speed observed in the ramp tests.

Additional information on the equipment and testing methodology can be found in Lima Jr. (2000), Melo (2001) and Viana (2003).

3 TEST RESULTS

3.1 *Soil-geosynthetic interaction in ramp tests*

Figures 3(a) and (b) show the variation of box displacement and tensile load at the geosynthetic extremity versus ramp inclination to the horizontal for tests with nonwoven geotextile GNW3 and soil A. In tests with the nonwoven geotextiles very little relative displacements between the box and the ramp were observed up to ramp inclinations close to 21°, which is the friction angle between the geotextiles and the ramp surface in these tests. For the interface GNW3-soil A, sliding of the soil on the geotextile occurred for a ramp inclination of approximately 32^o. The pattern of variation of box displacement with ramp inclination is very non linear and it is important to note that part of the displacement of the box may have been caused by distortion of the geotextile layer. As a fibrous soft material, nonwoven geotextiles can experiment some shear distortion before slide occurs along the interface. Distortion of the geotextile layer in a pure shear mode may be responsible for a significant fraction of the total box displacement at the early stages of the test. Displacements due to distortion and extension of the geotextile layer may be sufficient to cause cracks in compacted clay layers overlying the geotextile. Tests with the same geotextile and soil B (coarser sand) showed that higher box displacements were observed in tests with soil A (finer sand) than in tests with soil B. It was also observed that the stiffer the geotextile the smaller the box displacement at failure of the interface.

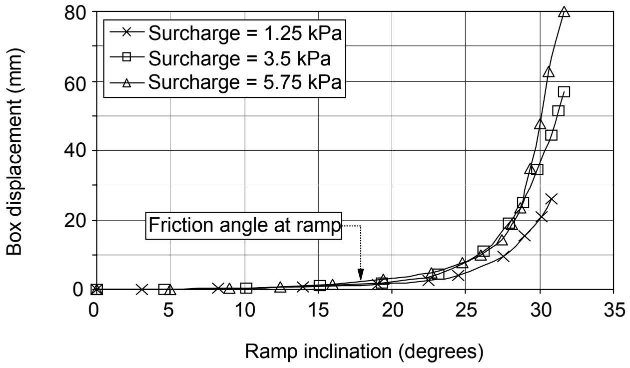
Table 2 Characteristics of the geosynthetics.

Geosynthetic code(1)	M_A(2) (g/m^2)	t_G(3) (mm)	T_{max}(4) (kN/m)	ε_{max}(8) (%)	J(9) (kN/m)
GNW1	100	1.0	7	50	13
GNW2	200	2.0	12	50	25
GNW3	300	2.6	20	50	45
GNW4	600	4.5	37	50	70
GNW5	200	2.2	12	60	22
GG1(6)	250	1.1	20	12.5	200
GM1	1380	1.0	14(7)	350	6.5(10)
GM2	1900	2.0	33(7)	700	430(11)
GM3	950	1.0	33(7)	700	260(11)
GM4	950	1.0	33(7)	700	260(11)
GM5	940	2.0	11(7)	100	87.5(12)

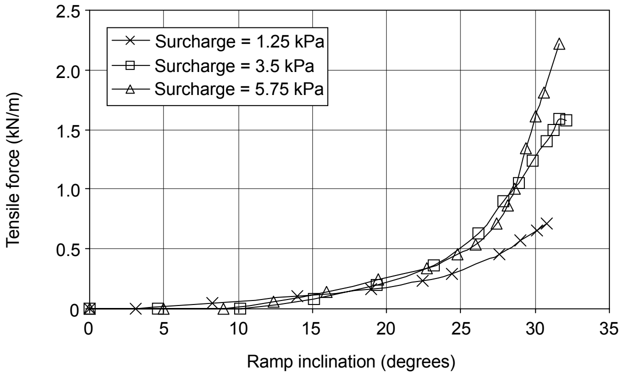
Notes: (1) Geosynthetic codes: GNW = G(geotextile) + NW (nonwoven), GG = geogrid, GM = geomembrane; (2) M_A = mass per unit area; (3) t_G = geosynthetic thickness; (4) T_{max} = tensile strength from wide strip tensile tests; (5) Longitudinal and transversal directions; (6) Aperture sizes equal to 20 x 20mm; (7) Stress at failure in MPa; (8) ε_{max} = tensile strain at failure from wide strip tensile tests; (9) Secant stiffness at ε = 10%; (10) Tensile modulus for ε = 100%, in MPa; (11) Tensile stiffness in MPa; (12) Secant tensile modulus at 12%, in MPa.

Figures 4(a) and (b) show results of tests with geomembranes GM1 and GM2 and soil B, where it can be observed the influence of the geomembrane stiffness on the mobilised box displacements. As observed in the tests with geotextiles, there is also a general trend of smaller box displacements at failure for smaller stress levels. It is important to note that the more extensible geomembrane (GM1) presented a considerably greater displacement response than the stiffer geomembrane (GM2) after the sliding along the geomembrane-ramp interface has occurred. The failure for the interface soil B-GM1 is more abrupt than that for the interface soil B-GM2.

The results obtained for tests with the rough HDPE geomembranes GM4 and clayey soil C are shown in Figures 5, in terms of box displacements and tensile loads versus ramp inclination. Geosynthetic forces and box displacements were considerably greater in these tests than those observed in tests with sand and smooth geomembranes (Figure 4b). This can be attributed to the greater interaction between the rough geomembrane and the clayey soil. The displacements of the box at failure were also greater in tests with soil C and the rough geomembrane than those obtained in tests with the smoother geomembranes and the same soil. This may be due to the amount of bond between the clayey soil and the rough geomembrane that caused greater distortions in the soil at the soil-geomembrane interface. The roughness of the surface of geomembrane GM4 makes failure to take place in the soil, causing the box displacements to be mainly controlled by soil deformation.



(a) Box displacements versus ramp inclination

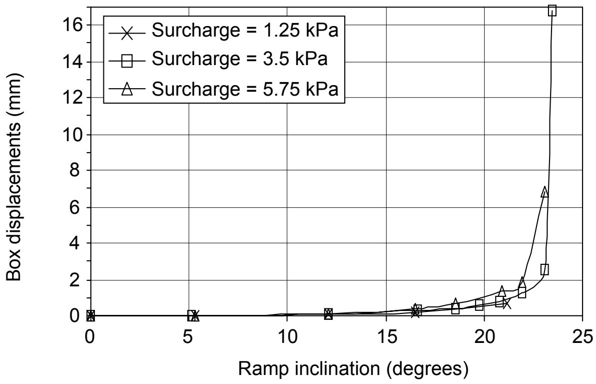


(b) Tensile force versus ramp inclination

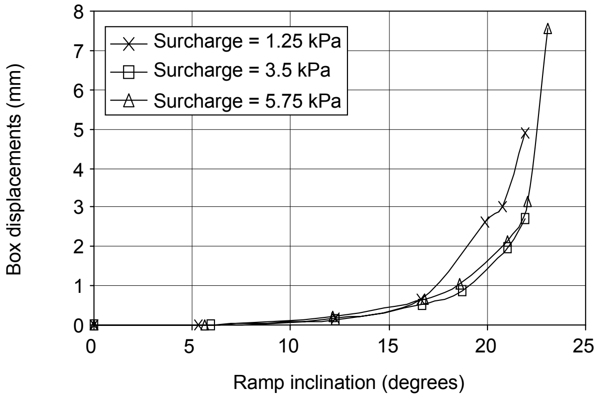
Figure 3 Test results for geotextile GNW3 and soil A.

Figures 6(a) and (b) show the variations of maximum box displacements and mobilised geotextile forces immediately before failure of the interface for tests with geotextiles GNW2 to GNW4 and soils A and B. Figure 6(a) shows that the greater the geotextile tensile stiffness the smaller the displacement immediately before failure. For the same geotextile, the maximum displacements were smaller for tests with the coarser sand (soil B) than with the finer sand (soil A). It can also be noted that the greater the geotextile tensile stiffness the greater the mobilised tensile force at its extremity just before interface failure.

The variations of maximum box displacements and mobilised geomembrane forces immediately before failure of the interfaces for geomembranes GM1, GM2 and GM4 and soil A to C are summarised in Figures 7(a) and (b). The marked influence of the geomembrane stiffness on the box displacements can also be observed (note the logarithm scale of the vertical axis of Fig. 7a), with the greater displacements occurring for geomembrane GM1 (PVC). The pattern of variation of mobilised geomembrane forces with the surcharge is typically linear (Fig. 7b). It can be noted that the geomembrane stiffness and the type of soil influenced the geomembrane loads, with the greatest values being observed for tests with soil C.



(a) Interface geomembrane GM1-soil B



(b) Interface geomembrane GM2-soil B

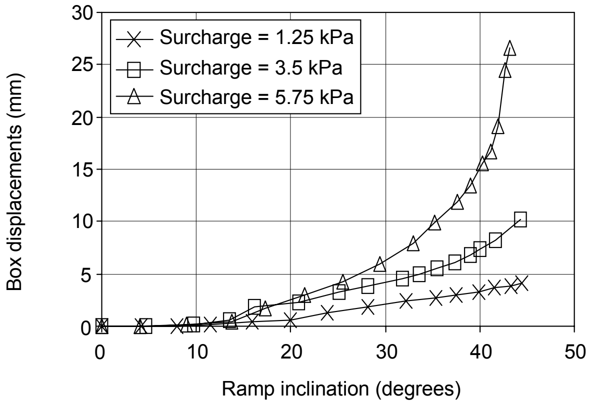
Figure 4 Test results for geomembranes GM1 and GM2 and soil B

Figure 8 shows the failure envelopes obtained for tests with geomembranes GM3, GM4 and GM4 and soil B. As commented earlier in this paper, these are HDPE geomembranes with different surface characteristics. GM3 has a smooth surface, while GM4 and GM5 have different roughness characteristics. The results in Figure 8 show the influence of surface roughness in increasing the friction angle between soil and geomembrane by approximately 5 degrees. The different roughness conditions for geomembranes GM4 and GM5 did not yield significant differences in the interface friction angle obtained.

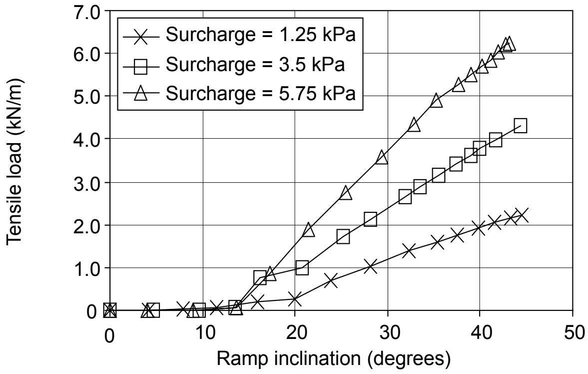
3.2 *Influence of the presence of a geogrid layer on the geomembrane*

The influence of the presence of a geogrid or a geotextile layer on the geomembrane on box displacements and mobilised tensile forces was also investigated. For these tests the thickness of the soil layer (soil B) was 0.2m (with no surcharge on its top). The test arrangements used in this series of tests are schematically shown in Figures 9(a) to (c).

Figure 10 shows the displacements of the box with ramp inclination for tests with soil B and three different arrangements: (1) test with geomembrane GM3 only (type of arrangement shown in Fig. 9a), (2) test with the same geomembrane and geogrid GG1 directly on it (type of arrangement in Fig. 9b), and (3) test with geotextile GNW5 between grid GG1 and geomembrane GM3 (Fig. 9c). It can be observed that the presence of the geogrid on the geomembrane increased considerably the ramp inclination at failure. When the system comprised the geogrid installed on geotextile GNW5 on GM3, the ramp inclination at failure increased even more and the box displacements were considerably smaller than those observed in the tests with the geomembrane alone or with the geomembrane underneath the geogrid layer.



(a) Box displacements versus ramp inclination

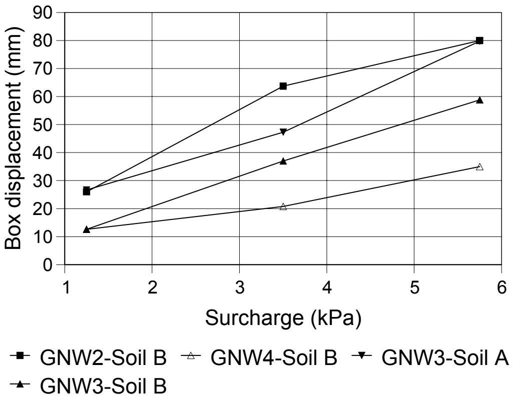


(b) Tensile force versus ramp inclination

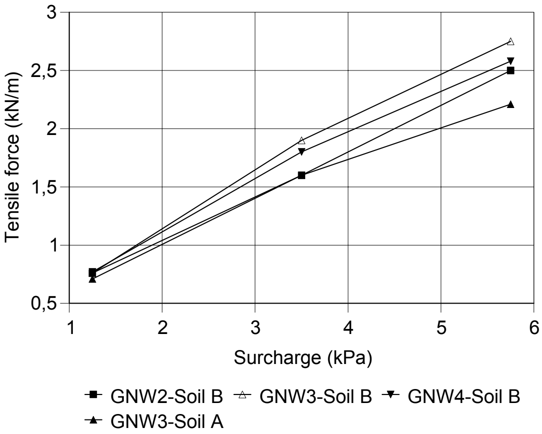
Figure 5 Test results for geomembrane GM4 and soil C

From the results in Figure 10 and comparing the ramp inclinations at failure for each of the systems (Figures 9a to c) one can estimate the increase of safety factor of the lining system due to the presence of the geogrid or the geogrid and the geotextile on the geomembrane, taking the inclination of the system comprising the geomembrane only (Fig. 9a) as a reference. Doing so, for the same ramp inclination at failure of the system with the geomembrane only, the presence of the geogrid on the geomembrane would increase de factor of safety from unity to 1.3. For the case of geogrid and geotextile on the geomembrane, the factor of safety would be increased to 1.42.

Figure 11 shows the variations of mobilised tensile forces in the geomembrane in ramp tests with soil B, under the following conditions: (1) test with geomembrane GM3 only, (2) test with geogrid GG1 on GM3 and (3) test with geogrid GG1 on geotextile GNW5 on GM3. The results show that the geomembrane force is a function of the adherence between the different interfaces. The mobilisation of geomembrane force in the test with the geomembrane only was very linear after a ramp inclination of 12°. For the test with geogrid GG1 on GM3 a rather steady geomembrane force was achieved after a ramp inclination of 24°, which coincides with the friction angle between the geogrid and the geomembrane, indicating that the change of pattern of variation of geomembrane force with ramp inclination at this stage was as consequence of the sliding along the geogrid-geomembrane interface. It can also be noted that the system incorporating geotextile between the geogrid and the geomembrane was the one that led to the smaller values of mobilised tensile forces in the geomembrane. The use of geogrids inside the soil mass at different elevations above the geomembrane can cause additional substantial reductions in geomembrane forces and this type of situation is discussed in Palmeira et al. (2003).



(a) Box displacements



b) Geotextile forces

Figure 6 Displacements and loads immediately before failure of the interface – tests with geotextiles and soils A and B

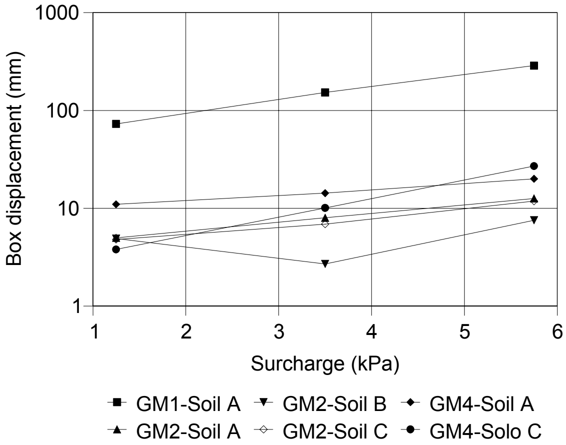
4 CONCLUSIONS

This paper presented a study on the use of a large scale ramp test for the study of interaction between soils and geosynthetics under low stress levels, compatible to those found in slopes of waste disposal areas. The main conclusions obtained are summarised below.

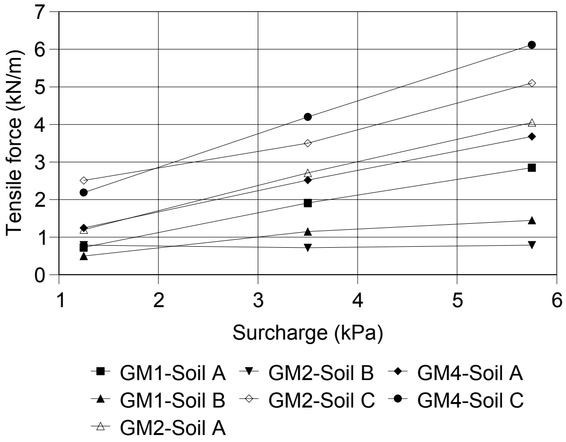
The ramp test is a useful tool for the evaluation of soil-geosynthetic and geosynthetic-geosynthetic interaction, providing values of interface strength parameters under condition closer to the field situation. It can also be used complementary to direct shear tests when tests under high and low stress levels are required.

The deformability of the soil-geosynthetic system is a function of the type of soil and type of geosynthetic tested.

The geosynthetic tensile stiffness is particularly relevant for the magnitude of displacements mobilised during the test. The variation of box displacements with ramp inclination is also a function of the characteristics of the interfaces tested. Tests with sand and a smooth PVC geomembrane showed a sudden failure mechanism, rather different from what was observed in the tests with the HDPE geomembranes. Rough geomembranes presented significantly higher adherence with soil than smooth ones. In spite of the differences between surface roughness conditions for the two different rough geomembranes tested, little difference was observed between the friction angles between these rough geomembranes and one of the sands tested.



(a) Box displacements



(b) Geomembrane forces

Figure 7 Displacements and forces immediately before failure

The use of a geogrid layer on the geomembrane reduced the mobilised displacements during the tests and yielded to a considerably higher ramp inclination at failure. The mobilised tensile force in the geomembrane was also reduced due to the presence of the geogrid. An even greater contribution to the reduction of geomembrane forces and system deformability was achieved when a geotextile was installed between the geogrid and the geomembrane.

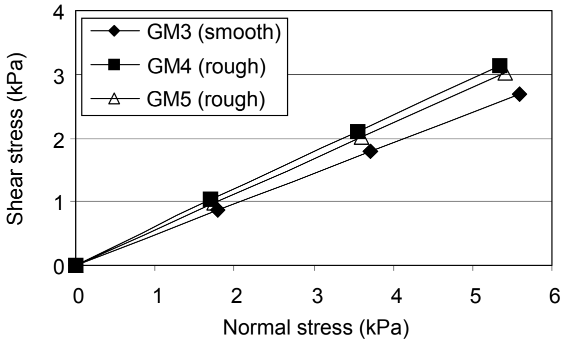
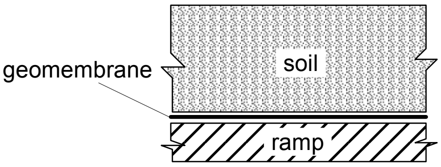
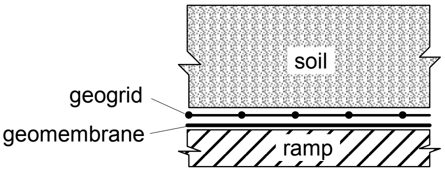


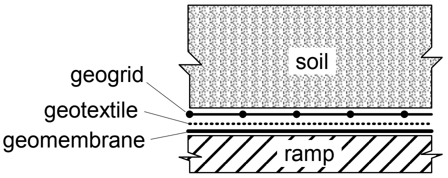
Figure 8 Failure envelopes for tests with geomembranes GM3 to GM5 and soil B.



(a) Tests with geomembrane only



(b) Tests with geogrid and geomembrane



(c) Tests with geogrid, geotextile and geomembrane

Figure 9 Arrangement for the tests with geomembrane, geogrid and geotextile.

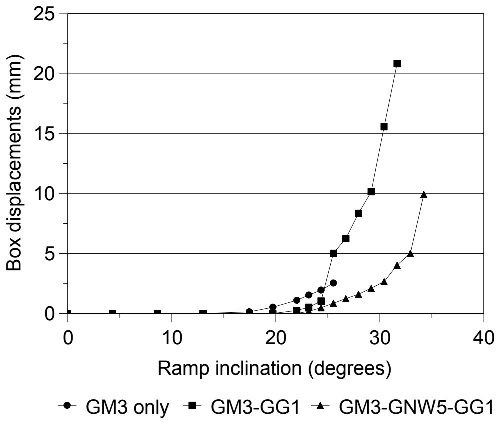


Figure 10 Box displacements in tests incorporating geogrid and geotextile on the geomembrane

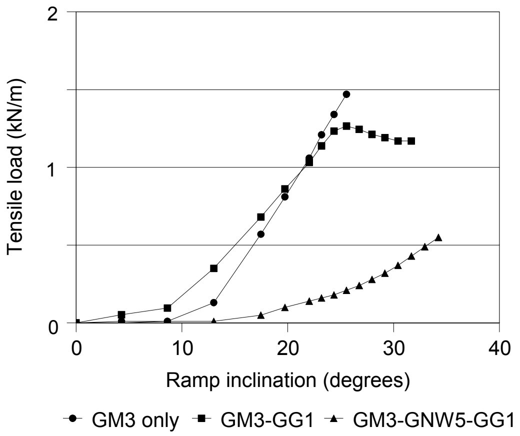


Figure 11 Geomembrane forces in tests incorporating geogrid and geotextile on the geomembrane.

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