Landmarks in Earth Reinforcement, Ochiai et al (eds),
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Design and development of inclined plane test on geosynthetics

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ABSTRACT: This paper presents experimental results from tests on geosynthetic/geosynthetic and sand/geosynthetic interfaces performed with an inclined plane apparatus designed in conformity with the European Standard prEN ISO 12957-2. More than 240 tests have been carried out, investigating almost all the interfaces that may occur in a landfill. The test results have been elaborated in order to make them comparable with direct shear tests results in a σ - τ plane. It is shown that the friction angles obtained by inclined plane tests are always lower than the ones obtained by direct shear tests for the same applied normal stress.

1 INTRODUCTION

In the design of geotechnical works there is always the need to analyze the stability conditions. This paper is focused on applications for geosynthetics where the potential sliding surfaces occur along interfaces between different materials placed on an inclined substratum. In particular, problems connected with landfill final cover systems stability have been considered: these structures present, from the upper surface layer to the lower gas collection layer, many possible surfaces along which sliding can occur. Therefore a fundamental point for the designers is the knowledge of frictional parameters between different types of geosynthetics and soil, derived from tests representing in situ conditions and variables. Many authors maintain that conditions characterised by low normal stresses cannot be represented by the direct shear test since it yields too high friction angle values, because of its inability to work well in this low range of forces. The need for a more suitable test method has caused the development of a new test called inclined plane. Therefore a new inclined plane apparatus has been designed and developed in the Tenax Laboratory in Viganò (Italy), with the aim of: 1) verifying the adequacy of the apparatus itself and in general of the test method; 2) comparing the results of the two tests (inclined plane and direct shear), and find their limits of applicability. The design of the inclined plane apparatus and the definition of test procedures have been carried out following CEN/TC 189 indications included in the European Standard prEN ISO 12957-2. Lacking any experience about this standard, during the development of the research a critical view has been maintained with the purpose to find any possible improvement to the inclined plane apparatus.

2 EXPERIMENTAL PROGRAM

Products and interfaces to be tested have been chosen with reference to landfill final cover systems. For soil-geosynthetic interfaces the soil used is a standard sand in accordance with EN 196-1, dried to a moisture content of less than 2 % and compacted to a density of 1.7 Mg/m^3. The tested geosynthetics and their main characteristics are summarized in Table 1.

3 INCLINED PLANE TEST APPARATUS

The apparatus (Figg. 1 to 5) consists of a 680 mm x 450 mm x 15 mm tilting table provided with two long screws which allow the plane to be set perfectly horizontal before the beginning of every test. Above it the lower box is placed: its internal dimensions are 400 mm x 325 mm x 100 mm; on its back side (see Fig. 3) there is the clamping system that allows to fix the geosynthetics: it consists of two bars with parallel series of holes where the rear side of the geosynthetic specimen has to be screwed down. The upper box has internal dimensions of 300 mm x 300 mm x 130 mm: it is fitted with rollers which bear on runners fixed on the lower box outer walls.

The normal force application system consists of a rigid plate and a frame placed on it through a circular section guide (see Fig. 1 and 5) which carries the weights clasped to the supports at the bottom. This system is able to be always vertical and passing through the center of gravity of the upper box. The normal forces applied produce the required normal stresses of 5, 10 and 25 kPa.

The tilting table lifts up at an angular speed of 3°/min. The rising device consists of an hydraulic

Table 1. Tested products

Products	Polymer	Symbol
Tessilbrenta Geotess TC/PP	PP	GTX 1
Tessilbrenta Geotess TC/PP	PP	GTX 2
Bidim S 61	PP	GTX 3
Geofabrics MP 200	PP	GTX 4
Du Pont Typar SF 40	PP	GTX 5
Amoco Propex 6061	PP	GTX 6
Agru HDPE Smooth	HDPE	GMB 1
Agru HDPE Rough	HDPE	GMB 2
Agru HDPE Micro spikes	HDPE	GMB 3
Agru HDPE Medium spikes	HDPE	GMB 4
Agru HDPE Big spikes	HDPE	GMB 5
Flag Flagon C/SL	PVC	GMB 6
Cover Top 32	LDPE	GMB 7
Tenax TNT 450	HDPE (GNT) PP (GTX)	GCD 1
Tenax TNT 600	HDPE (GNT) PP (GTX)	GCD 2
Tenax TNT 900	HDPE (GNT) PP (GTX)	GCD 3
Tenax TNT 1200	HDPE (GNT) PP (GTX)	GCD 4
Tenax Tendrain 1300/2	HDPE (GNT) PP (GTX)	GCD 5
Tenax Multimat R 110	PP (GEC) PET (GGR)	GEC 1
Tenax Multimat 100	PP	GEC 2
Tenax TT SAMP 045	HDPE	GGR 1
Tenax TT SAMP 160	HDPE	GGR 2
Tenax TT SAMP 201	HDPE	GGR 3
Tenax TT SAMP 401	HDPE	GGR 4
Tenax LBO SAMP 220	PP	GGR 5
Tenax CE450	HDPE	GNT 1
Tenax CE 600	HDPE	GNT 2
Laviosa Geobent STD 50	PET(GTXW) PP (GTXNW)	GCL 1
Laviosa Geobent HT 2450	PP (GTX W) PP (GTX NW)	GCL2

ram connected to the table by a shafting chain whose vertical movement is made horizontal by a cogwheel (Figure 2).

The displacement measuring device is a transducer (LVDT) connected to the rear wall of the upper box (Figure 3) through an inextensible wire. The ram and the transducer are connected to a multi-axes servo-hydraulic digital actuator, able to handle both data processing and control, up to 4 axes, either independently or combined between themselves, by controlling them in a feedback closed loop. For tests involving Geosynthetics with full surface (without apertures), like Geotextiles and Geomembranes, the lower box has been filled not with sand, but with a 400 mm x 325 mm x 97 mm block of wood, on which some plates of different thickness (1-3 mm) are laid to maintain a 0.5 mm gap between the fixed geosynthetic and the base of the upper box.

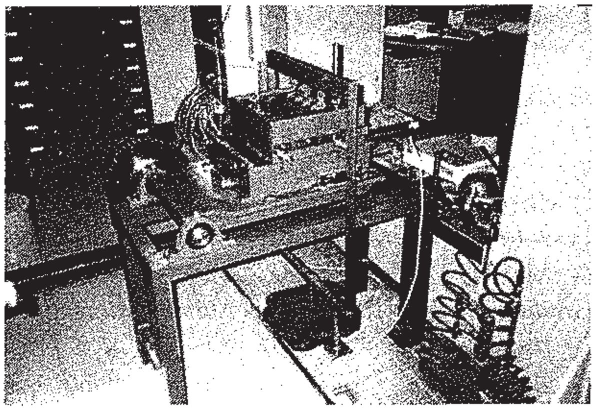

Figure 1. Inclined plane testing apparatus.

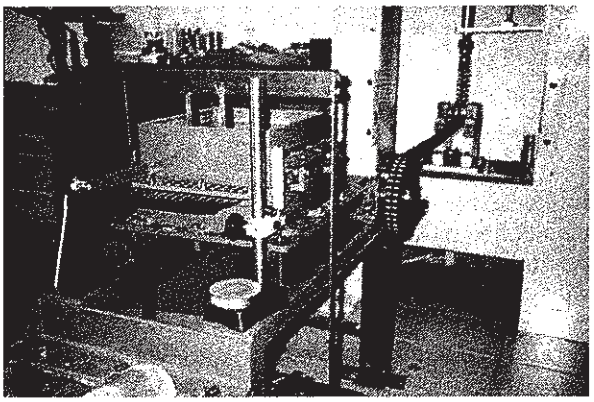

Figure 2. Start of an inclined plane test.

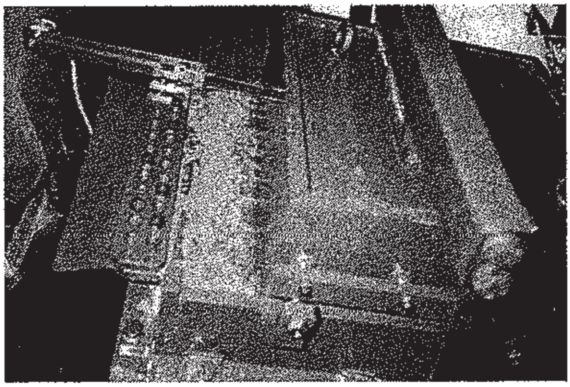

Figure 3. Detail of the clamping system and the movement transducer.

The testing of specimens with open structures requires the filling of the lower box with the soil. Two values of internal soil depth H_s in the upper box have been assumed: 100 mm and 50 mm, with the aim of observing its possible influence on the test results.

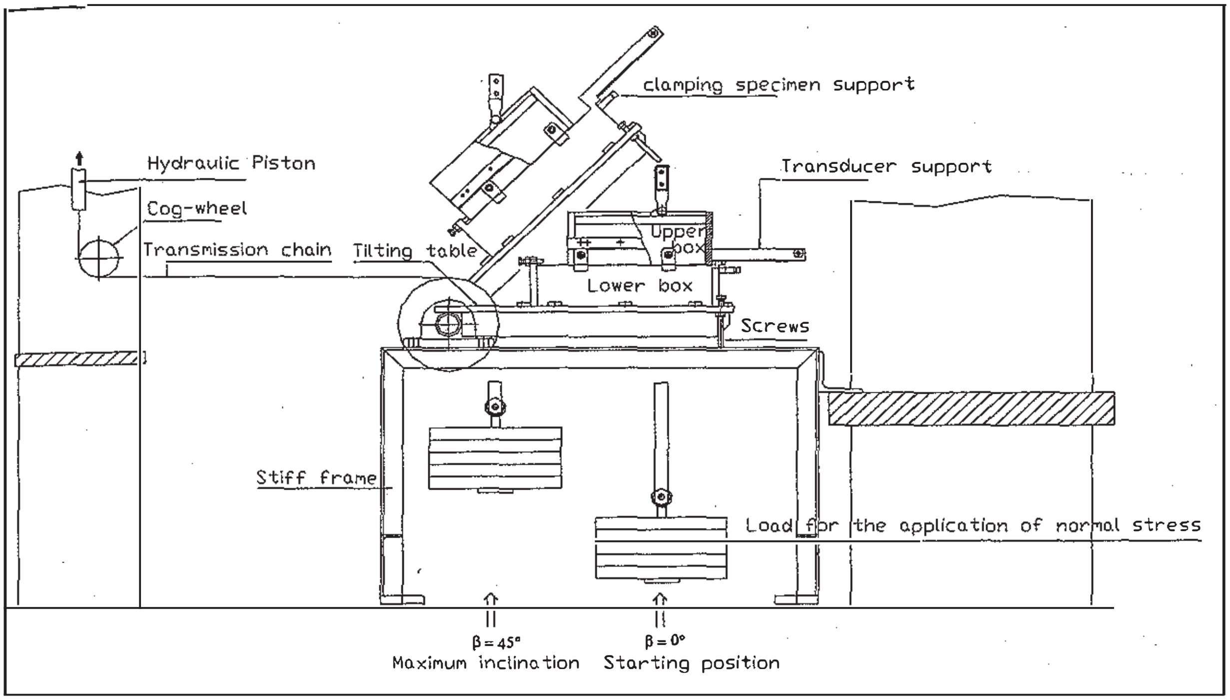

Figure 4. Cross section of the inclined plane test apparatus.

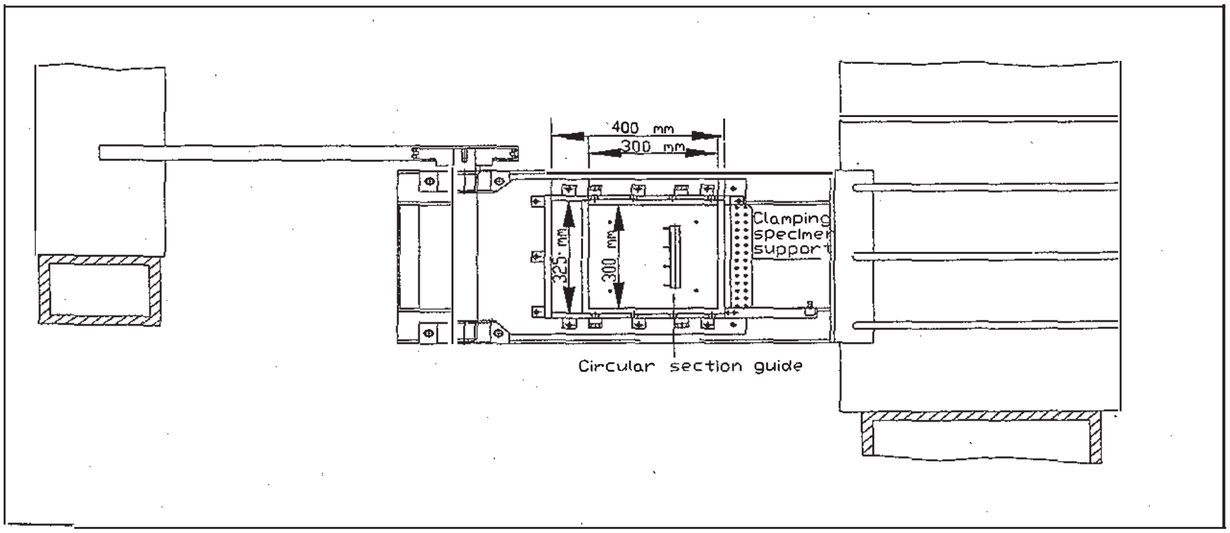

Figure 5. Plan view of the inclined plane test apparatus.

4 DIRECT SHEAR TEST APPARATUS

This apparatus consists of two rigid metal boxes, each one containing one of the two materials to be tested (Figure 6). The upper box remains steady during the tests, standing on four supports fixed to the plane of the hydraulic testing machine: its dimensions are 316 mm x 316 mm x 100 mm. The elevation of this box is adjustable by means of calibrated spacers which are inserted between the supports and the box itself. During the test, the 670 mm x 470 mm x 225 mm lower box moves on steel rollers standing on the plane of the testing machine at a constant velocity of 1 mm/min. The movement device consists of an hydraulic ram connected to the front wall of the lower box by a threaded pin whose vertical movement is made horizontal by a cog-wheel (this hydraulic ram is the same which produces the tilting of the inclined plane apparatus). The dimensions of the lower box have been established considering the possibility to carry out also performance tests using site specific soils. The vertical force is applied by means of an hydraulic piston which provides constant loading. The normal forces applied produce the normal stresses of 25, 50 and 100 kPa, suitable for a

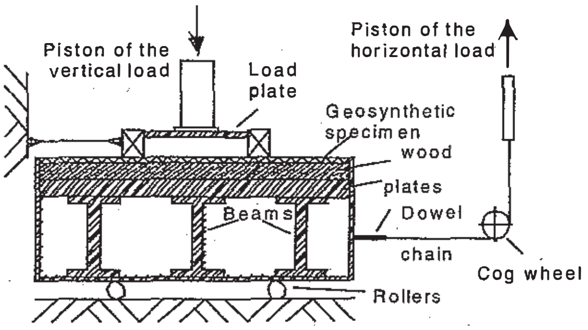

Figure 6. Scheme of the direct shear test apparatus.

comparison with inclined plane test. Both the pistons are connected to the multi-axes servo-hydraulic digital actuator. Through transducers connected to the pistons, the system is able to control simultaneously their positions, loads and velocity, keeping them within very narrow variation intervals. To fix geosynthetics specimen to the lower box, a plywood board has been used. Geocomposites have been attached to the plywood board by means of self-tapping screws distributed along three edges of the sample; the screws are placed outside of the contact area between the two materials and this assures that they cannot influence the results. Screws are not placed on the last side of the specimen, in order to prevent, in the case of lengthening of the geosynthetic, that it could bulge or wave and cause an increase of friction.

5 TEST RESULTS

5.1 *Inclined plane*

Results are presented in Δs-β graphs (Figure 7), where Δs is the movement of the upper box during the test and β is the inclination of the tilting table which increases at a constant rate. From the analysis of these diagrams three kind of behavior can be distinguished, in accordance with results recorded in the preliminary research made for the development of the European standard (AA, VV, 1995). The graphs may be categorized in: a) "sudden death": a long period of no displacement followed, after a movement at least of 1-2 mm, by a sudden and steep increase of the differential ratio ds/dβ; b) "steps curve" where the angle of first movement and the angle of failure do not coincide and the graph is characterized by steps of variable dimension; c) "slow motion before sudden death" in which there is a larger displacement of the upper box before sudden failure.

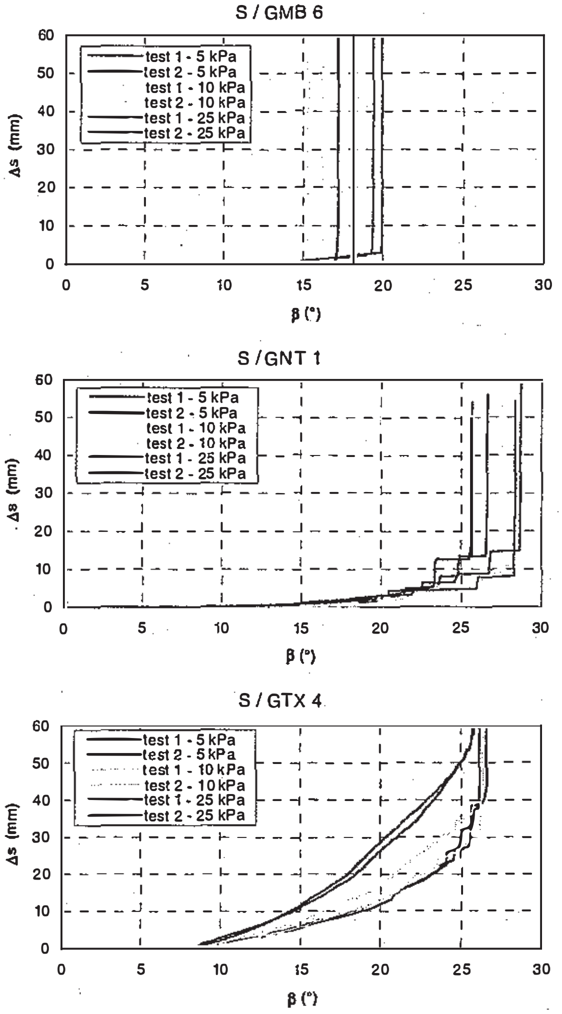

Figure 7. Typical results of inclined plane tests: top) "sudden death"; middle) "step curve"; bottom) "slow motion".

Graphs Δs-β allow to determine the angle of slippage (β), which is defined as the angle at which the displacement of the upper box is equal to 50 mm. From the value of the angle of slippage, the angle of friction φ needs to be calculated. For this purpose normal and shear stresses at the moment of the sliding have to be determined by means of the following equations:

$$\sigma_{np} = (9.81\ W \cos\beta)/(1000\ A) \qquad (1)$$

$$\tau = 9.81\ (W\ \mathrm{sen}\beta + f_{r(\beta)})/(1000\ A) \qquad (2)$$

$$\tan\phi = \tau/\sigma_{np} \qquad (3)$$

where: W = mass of soil, surcharge weights and any part of the upper box not supported on rollers, in kg; $f_{r(\beta)}$ = force required to restrain the empty upper box when the tilt table is inclined at an angle β; A = contact area (300 x 300 mm^2). After the calculation of the single values of φ, the results (τ and σ_{np}) are plotted in the σ-τ plane in order to compare in a better way inclined plane and direct shear tests.

In a different way from others Authors (Wasti & Ozduzgun, 2001) the normal stress used for the σ-τ

Table 2. Test results

Interface (S = Sand)	Test Conditions	Applied pressures (kPa)	ϕ (°)	a (kPa)
S/S	H	5-10-15-20-25	24.69	0.76
S/S	D	5-10-15-20-25	29.39	0.61
S/GTX1	E	5-10	20.57	1.30
S/GTX2	A	5-10-25	25.22	0.33
S/GTX3	E	5-10	20.26	1.17
S/GTX4	A	5-10-25	24.47	1.2
S/GTX5	E	5-10	21.73	0.37
S/GTX6	E	5-10	12.34	1.60
S/GMB1	E	5-10-25	12.98	0.25
S/GMB1$_a$	E	5-10	13.34	0.73
S/GMB2	E	5-10-25	21.62	1.10
S/GMB2$_a$	E	5-10	15.90	2.17
S/GMB3	E	5-10	21.79	1.10
S/GMB3$_a$	G	5-10	9.97	1.13
S/GMB4	E	5-10	21.84	0.63
S/GMB4$_a$	G	5-10	16.98	1.36
S/GMB5	E	5-10	18.91	1.05
S/GMB5$_a$	G	5-10	10.44	0.99
S/GMB6	A	5-10-25	20.92	0.02
S/GMB7	E	5-10	16.37	0.29
S/GCD1	E	5-10-25	22.55	0.53
S/GCD1	A	5-10-25	26.55	1.06
S/GCD1	A (wet)	5-10-25	27.97	0.88
S/GCD3	E	5-10-25	24.85	0.07
S/GCD4	E	5-10-25	21.54	0.77
S/GEC1	D	5-10-25	28.36	0.89
S/GEC2	D	5-10-25	28.31	1.05
S/GGR1	C	5-10-25	26.80	0.76
S/GGR2	C	5-10-25	24.66	0.56
S/GGR3	G	5-10-25	23.39	0.22
S/GGR4	C	5-10-25	24.06	0.52
S/GGR5	C	5-10-25	28.20	0.74
S/GNT1	C	5-10-25	29.20	0.69
GCD1/GMB1	I	5-10	11.09	0.05
GCD1/GMB2	I	5-10	21.78	1.52
GCD2/GCL1	L	5-10-25	23.99	1.19
GCD2/GCL2	L	5-10-25	22.02	0.54
GEC1/GCD1	A	5-10-25	24.24	0.33
GEC1/GCD5	A	5-10-25	27.40	-0.18
GNT1/GTX2	I	5-10	15.96	1.15
GNT2/GTX2	I	5-10	20.77	-0.02

plot is not the initial normal stress (for example 5 or 10 kPa), but the normal stress calculated with Eq. (1) at the instant of failure slippage, characterized by a lower value. In fact, to the authors' opinion, even though the initial σ may be considered as a "test condition", it is more significant to use the normal stress on the interface at failure for determining the ϕ value. By getting three points for the three normal stresses, it has been possible to obtain the failure envelope line on the σ-τ graph and to evaluate the friction angle and the adhesion for soil-geosynthetic and geosynthetic-geosynthetic interfaces or cohesion for soil-soil interfaces. The results are summarized in Tab. 2, where the different test conditions can be found in Tab. 3.

Table 3. Test conditions

Test conditions	Soil Depth Hs (mm)	Lower box content	Fixing specimen
A	50	Block of wood	Yes
B	50	Block of wood	No
C	50	Soil	Yes
D	50	Soil	No
E	100	Block of wood	Yes
F	100	Block of wood	No
G	100	Soil	Yes
H	100	Soil	No
I	-	Block of wood	Yes
L	-	Soil	No

5.2 *Direct shear tests*

The program of direct shear tests has included tests on three different interfaces, each representing one of the fundamental types of possible contacts which can be present in a real application, and in order to compare the results with the ones of the plane. The values of shear strength obtained by direct shear tests and the relative normal stresses have been represented in the σ-τ plane, where the friction angle and the adhesion or cohesion have been evaluated from the failure envelope line.

6 COMPARISON

Previously published works offer some examples of the comparison between these two test methods. Matichard et al. (1991) present values of friction angles obtained from direct shear tests that are larger than the ones from inclined plane tests. Wasti & Ozduzgun (2001), in particular for tests on rough HDPE geomembrane-geotextile interfaces, find both friction angle and adhesion values to be almost always higher by varying degrees for the direct shear test. Therefore, direct shear test envelopes lie above those of the inclined plane. Also in the present work the values from direct shear tests are always larger than the ones from inclined plane tests: the results obtained from comparison of tests on soil-geosynthetic and geosynthetic-geosynthetic interfaces yield important differences of 10-12 kPa for shear strength values and of 11°-15° for friction angle values.

Lower differences have been registered for the tests on soil-soil interfaces (respectively 2 kPa and 4°).

7 CONCLUSIONS

Measurements of shear resistance along interfaces between different materials, significant from the applicative point of view, have been made using a new inclined plane apparatus and a more experienced direct shear device. By means of the inclined plane method more than 240 test and 38 interfaces have been evaluated at the three initial normal stresses of 5, 10 and 25 kPa; the direct shear method was used to test 3 interfaces at the normal stresses of 25, 50 and 100 kPa, in order to afford a comparison with the same ones investigated by the previous apparatus. From inclined plane tests the following conclusions can be drawn:

- the friction angle tends to decrease with the increase of the initial normal stress;
- in soil-geosynthetic tests the position of the failure surface varies depending on the type of geosynthetic surface: for smooth surfaces it develops just at the interface, while for rough specimens it develops in the soil above the interface;
- the geosynthetic surface influences also the behavior of the displacement of the upper box;
- all the interfaces tested always present the final failure within 50 mm of relative movement of the upper box;
- tests with soil depth in the upper box $H_s = 50$ mm provide friction angles always higher than the tests with $H_s = 100$ mm, probably because the procedure with $H_s = 100$ mm creates an unbalanced distribution of the forces working on the interface, thus causing an advanced failure along the shear surface;
- taking into consideration the sensitivity of this apparatus and of this test method with regards to the boundary conditions, it seems fundamental to set all the test variables in order to assure repeatability and reproducibility of results.

From the comparison of the results of the inclined plane and the direct shear tests, the following conclusions can be drawn:

- friction angle values obtained by inclined plane tests are always lower than the ones obtained by direct shear tests;
- inclined plane test results shall be considered in modeling load conditions on slope, while values from direct shear tests cannot be considered correct for this situation;
- direct shear test has to be used for conditions characterized by loads on horizontal interfaces, for which inclined plane test produce too much conservative results;
- from the previous point it follows that the stability analysis of particular projects, like landfill cover systems, shall be performed considering friction angle and adhesion values determined by inclined plane, since this apparatus can model the actual conditions in a correct way, yielding more realistic results, which put the designer in favor of safety.

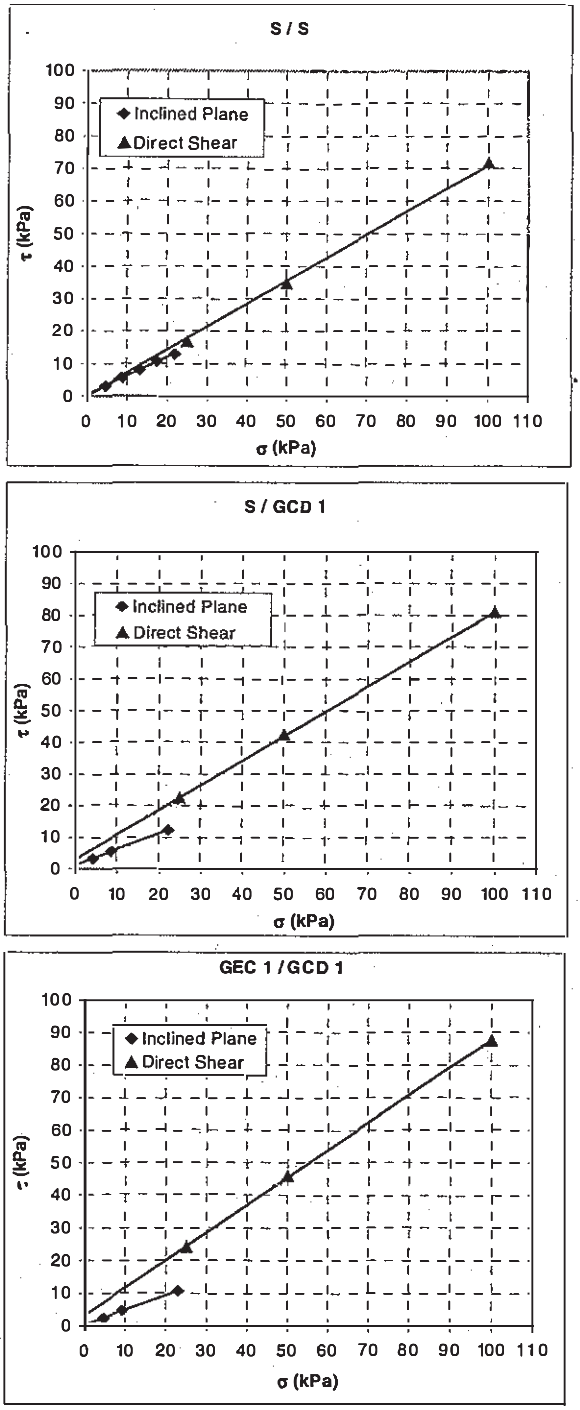

Figure 8. Comparison of results in the σ-τ plane

8 ACKNOWLEDGEMENT

This research program was carried out with the financial support of MURST (Italian Ministry for University and Scientific and Technical Research).

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