Consideration of Geosynthetic Tension in Interpretation of Data from Inclined Plane Tests

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Abstract. The inclined plane device is specifically adapted to assess the geosynthetic interfaces friction under low confinement conditions. The lack of the standardized procedure proposed by the European standard (EN ISO 12957-2 2005) for the determination of geosynthetic interface friction properties has been proven by many recent researches available in the literature.

These researches demonstrated the need for revising the standard displacement procedure since it seems to be poorly suited for many geosynthetics interfaces and because the high sensitivity of the determined friction angle to test conditions.

Geosynthetics of reinforcement interface properties were determined by carrying out inclined plane tests under low confinement adapted to landfill covers conditions. Interface friction angles $\left(\varphi^{stand}\right)$ were determined conformingly to the standardized displacement procedure and compared with those defined by a method known from the literature.

Then, interface friction angles were determined according to a new method called "tension procedure" which considers the measurement of the tension developed by the geosynthetic reinforcement during inclined plane tests.

Compared to previous data, the proposed method allows a new and more comprehensive interpretation of the inclined plane test since it pays attention to the different behavior of geosynthetics during tests.

This research demonstrates that the consideration of reinforcement tensions allows a more suitable comprehension of the mechanical behavior of soil-geosynthetic interface and a better representation of the in-situ behavior of the geosynthetic interface.

It appears that the mechanical behavior of the geosynthetic of reinforcement and the magnitude of the measured tension depended on the reinforcement characteristics specially the geosynthetic surface structure and the tensile stiffness (tensile modulus) J *(kN/m)*.

The determined friction angles, both in static $\left(\varphi^{stat}\right)$ and dynamic $\left(\varphi^{dyn}\right)$ inclined plane conditions, are lower than those calculated using the previous methods which allow a more accurate design of landfill cover systems.

1 Introduction

Geosynthetic interface friction angles can be determined using the modified direct shear box test and the inclined plane test following the European standard *EN ISO 12957-2 (2005)*.

Many recent studies indicated that the inclined plane is the more appropriate device for the measurement of geosynthetic interface friction angles under low normal stress (Gourc and Reyes-Ramirez 2004; Briançon et al. 2011; Stoltz et al. 2012; Carbone 2013).

However, these studies showed that friction angles measured following the European standard method is non conservative and suggested a revision of the standard testing procedure.

In fact, Gourc and Reyes-Ramirez (2004) demonstrated that standard friction angle φ^{stand} was assessed from a static analysis for conditions that were actually dynamic and proposed a "static – dynamic" procedure which defined a static φ^{stat} and a dynamic φ^{Dyn} friction angles.

The dynamic friction angle φ^{Dyn} was calculated taking into account the displacement acceleration γ of the upper geosynthetic during the non- stabilized displacement on the inclined plane.

However, it was difficult to determine graphically the acceleration γ especially for the interfaces involving geosynthetics having surfaces with significantly sized apertures and questions raised about the effect of the dynamic conditions on the interface properties in such cases.

Briançon et al. (2011) proposed a new method called "force procedure" where a cable connected the soil retaining box to a force sensor fixed on the inclined plane.

Stoltz et al. (2012) proposed a light modification of the "force procedure" by substituting the cable with a spring connecting the soil retaining box and the device frame.

The proposed procedure, called "residual friction procedure", allows the determination of the residual friction properties of geosynthetic interfaces in almost static displacement conditions.

The main disadvantage of both the "force procedure" and the "residual friction procedure" is that it allows only the determination of the residual interface properties φ^{res} which have an importance only in situations where failure may result due to large movement along the soil - geosynthetic interface. This situation is unlikely common in site conditions.

The prime importance in geosynthetic interface design should be given to static and dynamic interface friction angles since small displacements generally occur along the potential failure geosynthetic interface.

In order to assess the different geosynthetic interface friction angles at various kinematic conditions and to understand the temperature influence on the interface friction, Carbone (2013) conducted inclined plane tests according to a new test procedure called "unified inclined plane procedure".

This method is based on grouping the "static – dynamic procedure" of Gourc and Reyes-Ramirez (2004) and the "force procedure" of Briançon et al. (2011) in one unified procedure.

The "unified inclined plane procedure" seems to be a more suitable method since it allows the assessment of different interface friction angles in different kinematic conditions (static, dynamic and residual).

However, as well as the "static – dynamic procedure", this method remains unable to explain the difference between the transition phase extensions as recorded during the carried out tests;and it does not consider the mechanical characteristics of the tested geosynthetic when the geosynthetic interface friction angles are calculated.

From all these studies, it appears that the suggestion of a more accurate testing procedure for the inclined plane tests which allows a more precise measurement of geosynthetic interface friction angles is actually a pending question.

In this paper, all of the tests were conducted using an inclined plane available in the LTHE laboratory of Grenoble (France) which is designed in accordance with the European project of standardization (*EC Measurement and Testing Program Project 0169 –Task 3.2: Friction – 1996, 1997*).

Herein, four soil-geosynthetic of reinforcement interfaces were tested using the inclined plane in order to choose the most performing product in soil stabilization among two geotextiles of reinforcement and two geocomposites obtained by gluing two geomats to the previous geotextiles.

Interface friction angles were firstly calculated according the European standard method (*EN ISO 12957-2* 2005), and then by using the "static- dynamic" method of Gourc and Reyes-Ramirez (2004). The main disadvantages of these methods were discussed.

Furthermore, the interface friction angles were recalculated using a proposed method, called "tension procedure", which considers the reinforcement tension as a resistant force to the tangential shear stress along the slope.

2   Test Apparatus and Materials

Experimental tests were carried out using an inclined plane designed for characterizing the interaction mechanism at soil – geosynthetic interfaces (Fig. 1).

For each geosynthetic reinforcement tested, a sample of geosynthetic (*0.8* m *1.3* m) is fixed to the top of the inclined plane and filled with sand.

1:Displacement sensor
2:Retaining soil box
3:Geosynthetic of reinforcement
4:Rigid support platform
5: Pivot
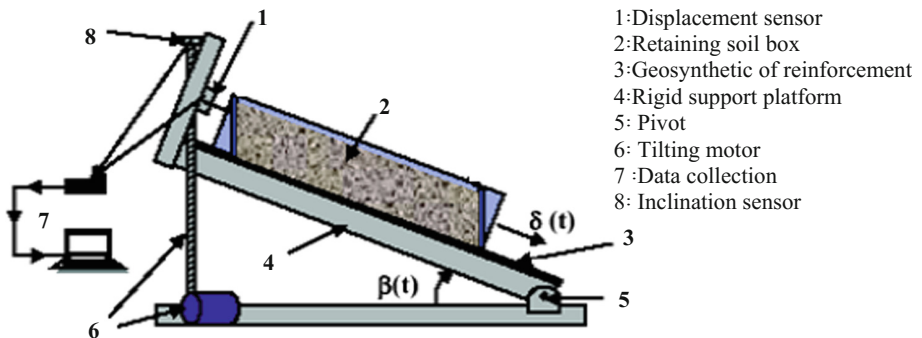6: Tilting motor
7 :Data collection
8: Inclination sensor

Fig. 1. Inclined plane device

A soil retaining box (Plexiglas) is placed on the geosynthetic sample and filled with 5 cm thick layer of soil and steel plates (metallic charges) to provide the initial normal stress on the soil-geosynthetic interface.

During the tests, the box slides along the plane on two guiding poles fixed at the both sides of the inclined plane. The contact between the guiding poles and the soil retaining box is assumed to be frictionless.

A displacement sensor, fixed to the rigid support of the plane and relied to the soil retaining box by a cable, measured the displacement of the box as the inclination angle of the plane grows.

Tests results were recorded by computer system and saved in an "xls" file format which registered data of inclination angle, soil retaining box displacement and time of test.

Four geosynthetic reinforcement materials have been tested (Fig. 2):

– Non – woven geotextile, reinforced with polyester fibers (*Gtr₁*).
– Woven geotextile, reinforced with black polyester fibers (*Gtr₂*).
– Geocomposite [*Gtr₁-Gmat₁*]: a polypropylenegeomat with *8* mm length fibers is glued on the geotextile *Gtr₁*.
– Geocomposite [*Gtr₂-Gmat₂*]: a polyester geomat with *6* cm length fibers is textured on the geotextile *Gtr₂*.
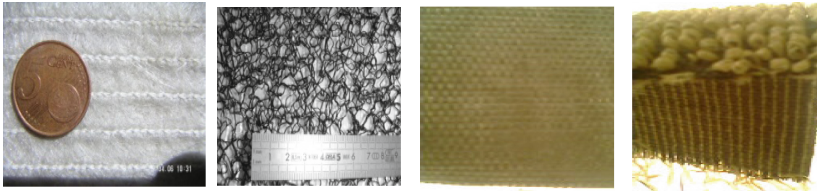
Geotextile *Gtr₁*   Geocomposite[*Gtr₁-Gmat₁*]   Geotextile *Gtr₂*   Geocomposite[*Gtr₂-Gmat₂*]

Fig. 2. Geosynthetic materials tested

Geomats are tridimensional geosyntheticsused at the soil-geotextile of reinforcement interface when the friction properties of this interface risks to be not sufficient in soil stabilization on steep slopes.

The used soil was a sand having an internal friction angle $\varphi = 35°$ and a water content $\omega = 6\%$.

Tests were carried out under an initial normal stress $\sigma'_0 = 7.5$ kPa resulting of *53* kg of soil and *40* kg of metallic charges placed in the retaining soil box.

At the beginning of the test, the inclined plane was ($\beta_0 = 0$). At this initial position, the displacement sensor indicated zero displacement ($\delta = 0$).

The inclined plane was then inclined at a constant rate ($d\beta/dt = 3°/min$) until obtaining a non-stabilized sliding of the soil retaining box on the platform corresponding to an inclination angle (β_s).

3   Test Results

Result repeatability was verified for each test and only the representative values of the inclination angles was used to calculate the interface friction angles.

For each soil – geosynthetic interface tested, results were presented as displacement (δ) versus slope angle (β) curve.

The ISO standard *12957-2* evaluates the interface friction angles $\left(\varphi^{stand}\right)$ for a sliding displacement $\delta = 50$ mm and for the following mechanical diagram (Fig. 3).
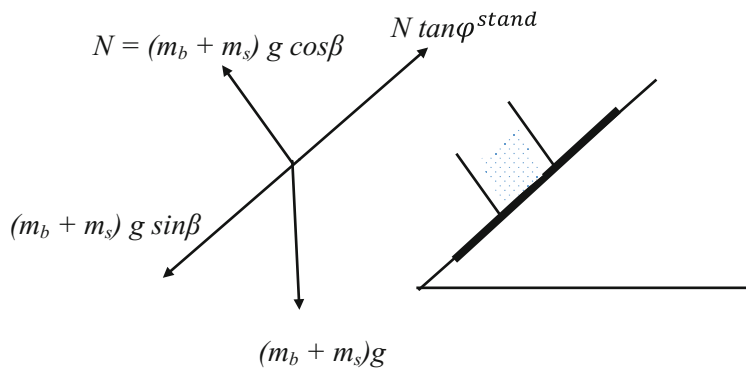
Fig. 3.   Forces acting on the soil-geosynthetic interface during the inclined plane test.

The interface friction angles were calculated for an inclination angle β_{50} corresponding to a box displacement of *50* mm using the equation:

$$tan\, \varphi^{stand} = \frac{(m_b + m_s) \cdot g \cdot sin\, \beta_{50}}{m_s . g . cos\, \beta_{50}} \qquad (1)$$

Table 1 summarizes the φ^{stand} values of the four tested soil – geosynthetic of reinforcement interfaces. Calculations were done using the following parameters:

m_b: soil retaining box mass (*28.8* kg).
m_s: metallic charges and soil masses (*93* kg).
N: normal reaction of the interface.

The placement of a geomat in the soil-geotextile interface improved considerably the interface friction since friction angles increases six (*6*) degrees for the first geotextile (*Gtr₁*) and height (*8*) degrees for the second geotextile (*Gtr₂*).

Table 1. φ^{stand} values determined for the tested interfaces

Structure de renforcement	β_{50} (°)	ϕ^{stand} (°)
Gtr₁	18	26.5
[Gtr₁-Gmat₁]	22	32
Gtr₂	17	25
[Gtr₂-Gmat₂]	22.5	33

However, as shown on Figs. 4 and 5, the displacement of the soil retaining box started at an inclination $\beta = 13°$ for the geocomposite [Gtr_1-$Gmat_1$] and $16°$ for the geocomposite [Gtr_2-$Gmat_2$]. This difference is due to the different behavior (deformability) of the tested geocomposites which is not considered by the standard method.
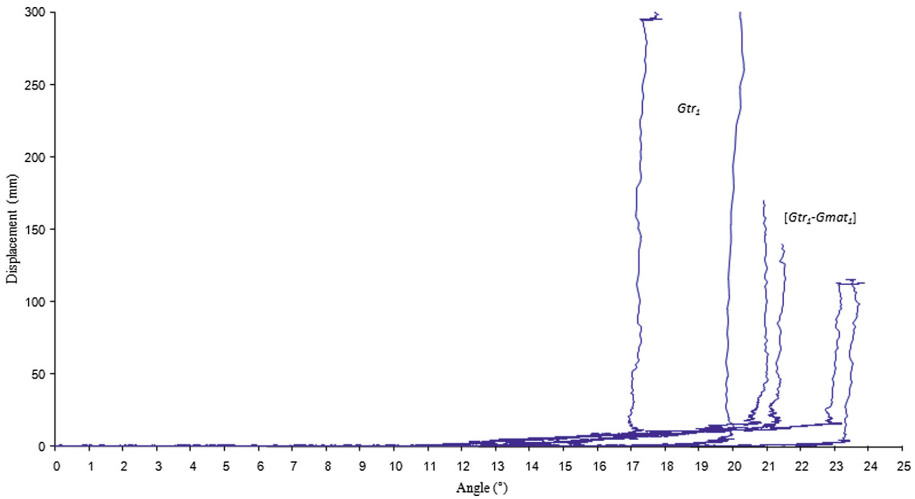
Fig. 4. Horizontal displacement (δ) versus inclination angle β for the interfaces soil - [Gtr_1-$Gmat_1$] and soil - Gtr_1
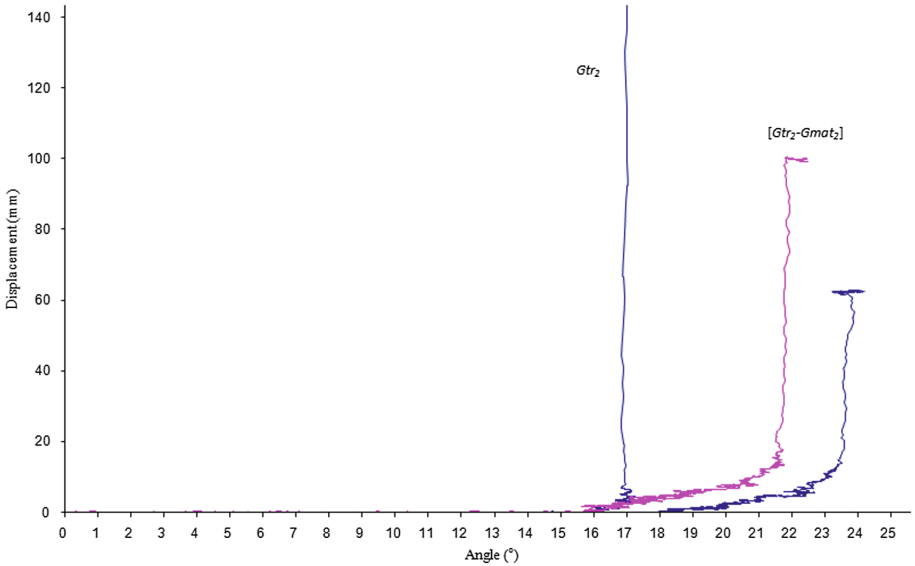
Fig. 5. Horizontal displacement (δ) versus inclination angle β for the interfaces soil - [Gtr_2-$Gmat_2$] and soil - Gtr_2

Moreover, evaluating the interface friction angle ϕ^{stand} for a plane inclination corresponding to a relative sliding displacement $\delta = 50$ mm not give relevant value of the friction angle since test conditions are not static, Gourc et al. (2008).

Consequently, many studies available in the literature suggested a revision of the standard procedure and tried to give a more comprehensive interpretation of the inclined plane test in order to deduce additional information which may be utilized valuably in interface behavior interpretation, (Gourc and Reyes-Ramirez 2004; Briançon et al. 2011; Stoltz et al. 2012 and Carbone 2013).

In the next section, inclined plane tests carried out are reinterpreted in accordance with the "static – dynamic procedure" proposed by Gourc and Reyes-Ramirez (2004) to prove the inadequacy of the current European test standard.

4   "Static-Dynamic Procedure" (Gourc and Reyes-Ramirez 2004)

This interpretation method distinguishes three phases during the inclined plane test (Fig. 6):

– A static phase: during which the soil retaining box is practically immobile ($\delta = 0$). This phase extends from the beginning ($\beta = 0$) of the test until the beginning of the movement of the retaining box over the inclined plane at the inclination angle β_0.
– A transitory phase: during which the soil retaining box move gradually downwards ($\beta_0 < \beta < \beta_s$).
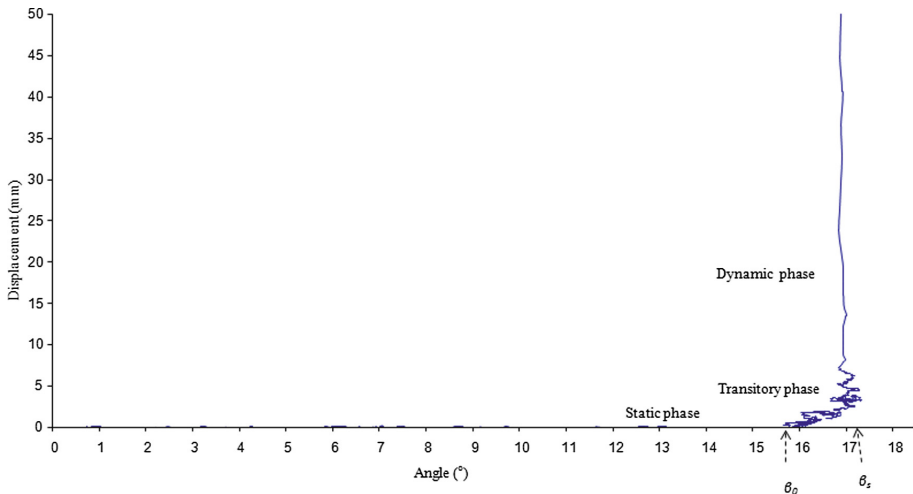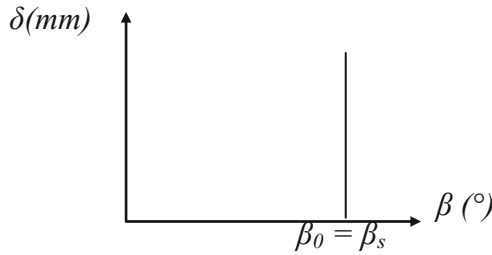

Fig. 6. Phases of the inclined plane test, Gourc et Reyes–Ramirez (2004).

Three types of transitory phases are possible and are function of the sliding mechanism of soil retaining box on the inclined plane:

- A non-stabilized sliding of the soil retaining box with a nonexistent transitory phase $(\beta_0 = \beta_s)$: a sudden sliding- abrupt displacement (Fig. 7).

Fig. 7. Non existent transient phase

- A gradual sliding - displacement which increases progressively with the plane inclination (β) (Fig. 8).
- A jerky sliding- displacement increasing in a "stick-slip" fashion (Fig. 9).
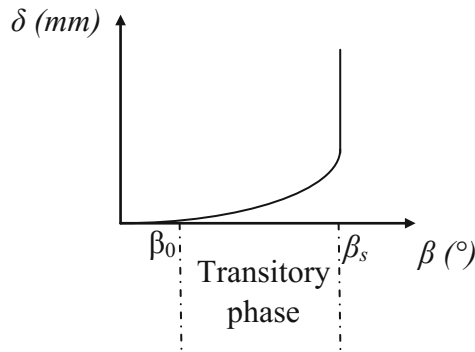

Fig. 8. Gradual sliding.

- A non –stabilized sliding phase where the soil retaining box is in a state movement with a constant acceleration γ.

The authors reported that the standard friction angle was not conservative since the adopted mechanical analysis was not conducted in dynamics although the soil retaining box is in a state of movement at the inclination β_{50} considered by the standard procedure.
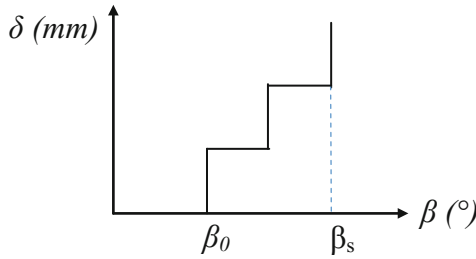
Fig. 9. Jerky sliding.

Consequently, two different interface friction angles were defined:

- Static friction angle ϕ^{stat} corresponding to the initialization of the movement ($\beta_0 \leq \beta \leq \beta_s$).

$$tan\,\varphi^{stat} = \frac{(m_b + m_s).g \cdot sin \cdot \beta_0}{m_s \cdot g \cdot cos\,\beta_0} \tag{2}$$

- Dynamic friction angle φ^{dyn} calculated in dynamic conditions when the soil retaining box enters in movement with constant acceleration ($\beta \geq \beta_s$).

The constant acceleration γ was determined graphically using the displacement δ/time t and displacement rate/time t graphs.

$$tan\,\varphi^{dyn} = \frac{(m_s + m_b) \cdot g \cdot sin\,\beta_s - (m_s + m_b)\gamma}{m_s.g.cos\,\beta_s} \tag{3}$$

Static and dynamic friction angles were calculated for the tested soil - geosynthetic interfaces (Table 2).

Table 2. Static and dynamic friction angles of the tested soil - geosynthetic interfaces

Geosynthetic of reinforcement	β_0 (°)	φ^{stat}(°)	β_s (°)	Displacement rate min and max (mm/s)	γ (ms^{-2})	φ^{dyn} (°)
Gtr_1	14	20	17	0.2/2.1	3.45 E-3	23.6
[Gtr_1-$Gmat_1$]	13	19	22	0.1/0.55	1.12 E-4	28.5
Gtr_2	16	23	17	0.2/6.6	1.6 E-3	23.6
[Gtr_2-$Gmat_2$]	16	23	22	0.2/0.62	1 E-4	29.6

The calculated friction angles φ^{stat} and φ^{dyn} were lower than the standard friction angle φ^{stand}.

It appears that the "static-dynamic" analysis of Gourc and Reyes–Ramirez (2004) allowed a more comprehensive interpretation of the soil -geosynthetic interface behavior and the determined interface properties were more conservative than the standard friction angle.

However, it was difficult to determine graphically the acceleration γ especially for the interfaces involving geosynthetics having surfaces with significantly sized apertures like geomats. The calculated displacement rates were very low for the two soil-geocomposite interfaces tested and questions raised about the effect of the dynamic conditions on the interface properties in such cases.

Moreover, different transitory phase extensions were remarked for the four geosynthetic interfaces tested. It extends 6° for the soil - [Gtr_2-$Gmat_2$] interface and 9° for the soil - [Gtr_1-$Gmat_1$] interface. This difference was not considered by the "static – dynamic procedure".

5   New Proposed Procedure: "Tension Procedure"

The inclined plane tests described above were carried out under an initial normal stress $\sigma'_0 = 7.5$ kPa.

The same geosynthetic samples were tested under lower initial stresses (4 and 5 kPa) in order to understand its influence on the tested geosynthetic interface behavior (Fig. 10).

Soil -[Gtr_1-$Gmat_1$] interface
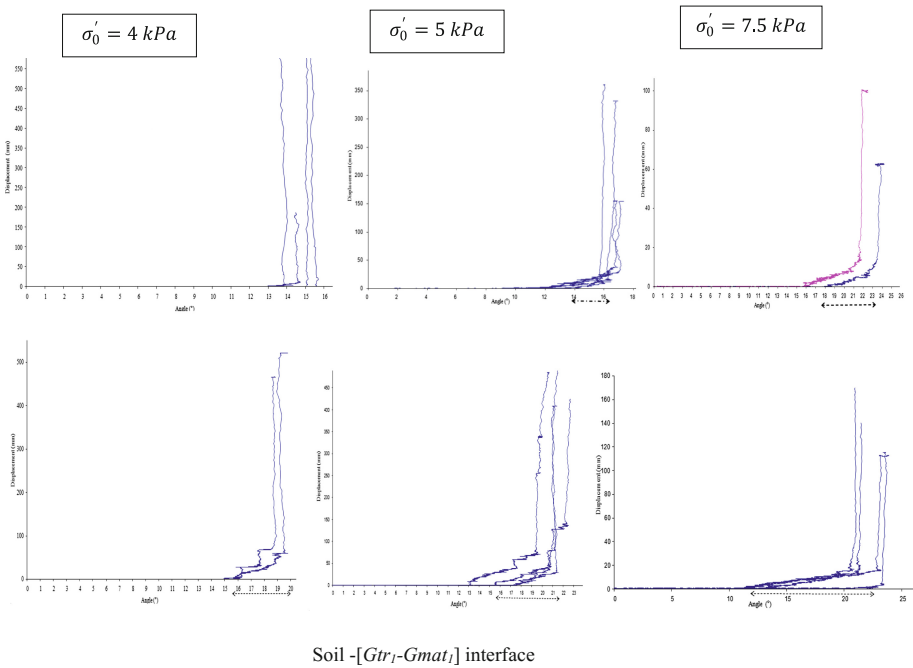
Fig. 10. Influence of the initial normal stress on the transitory phase extension of the tested soil - geocomposite interfaces.

Results displayed in Fig. 10 and Table 3 for the Soil - $[Gtr_1\text{-}Gmat_1]$ and Soil - $[Gtr_2\text{-}Gmat_2]$ interfaces indicate that the transitory phase extension increases when increasing the initial normal stress.

Table 3. Variation of the transitory phase extension with the initial normal stress

Initial normal stress (kPa)	Geosynthetic reinforcement	
	$[Gtr_1\text{-}Gmat_1]$	$[Gtr_2\text{-}Gmat_2]$
4	4°	Brutal sliding
5	7°	2°
7.5	12°	5°

It appears that the sliding mechanism (jerky, gradual or sudden) is not a constant behavior of geosynthetic interfaces as reported by Gourc and Reyes-Ramirez (2004) but also depends on the initially applied load on the tested interface and the geometric structure of the geosynthetic surface.

At the beginning of the test where test conditions are static ($0 \leq \beta \leq \beta_0$), the shear strength mobilization depends on the interface roughness.

Higher initial normal stress leads to higher mobilization of shear strength at the soil-geosynthetic interface and within the geosynthetics themselves as a tension transmitted to the geosynthetic anchorage at the top of the inclined plane.

The increase of the plane inclination β leads to an increase of the shear strength ($sin\beta$ increases) and a decrease of the shear resistance ($cos\beta$ decreases). Consequently, the tension mobilized by the geocomposites increases during the static phase of the test.

The mobilized tension F provides a geosynthetic deformation if this geosynthetic of reinforcement have not a sufficient tensile modulus (J)

$$F = J \times \varepsilon \tag{4}$$

Where:

J: tensile modulus of the geosynthetic of reinforcement (kN/m).
ε: geosynthetic deformation (dimensionless).

The sudden sliding- abrupt displacement is obtained in two cases:

– The first case when the initial normal stress is low and the low mobilized tension cannot provide the geosynthetic deformation. For $\beta = \beta_s$ the shear strength exceeds the interface shear resistance and the soil retaining box is forced to move on the inclined plane.
– The second case when the geosynthetic tensile modulus is very high and the relatively high mobilized tension cannot provide the geosynthetic deformation although the test is carried out under high initial normal stress.

A transitory phase is obtained from a plane inclination β_0 if the geosynthetic tensile modulus (J) is not sufficient to avoid geosynthetic deformation. In this phase, there is no displacement between the soil and the geosynthetic and test conditions can be considered as pseudo-static.

Consequently, the geosynthetic mobilized tension during an inclined plane test is an important force which should be considered as a resistant effort to the interface shear stress.

The non-consideration of the geosynthetic tension leads to an overestimation of the interface friction angle.

When carrying out the inclined plane tests described above which were conducted under an initial normal stress $\sigma' = 7.5$ kPa, the geosynthetic tension was measured by a force captor installed at the top of the inclined plane (Fig. 11).

Soil retaining box

Displacement sensor

Force sensor
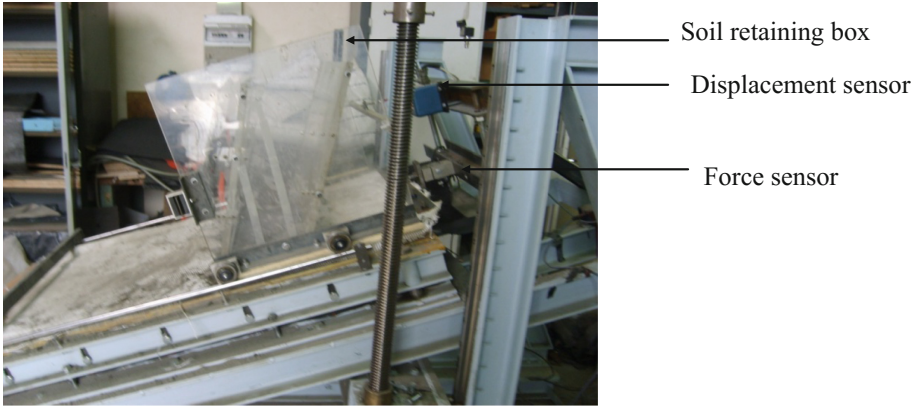
Fig. 11. Measurement of the geosynthetic tension during the inclined plane test.

To assess the geosynthetic mobilized tension during the inclined plane tests, the diagrams geosynthetic tension (F) versus displacement (δ) were presented for the four tested geosynthetic of reinforcement in addition to the classic diagrams displacement (δ) versus inclination (β) (Fig. 12).
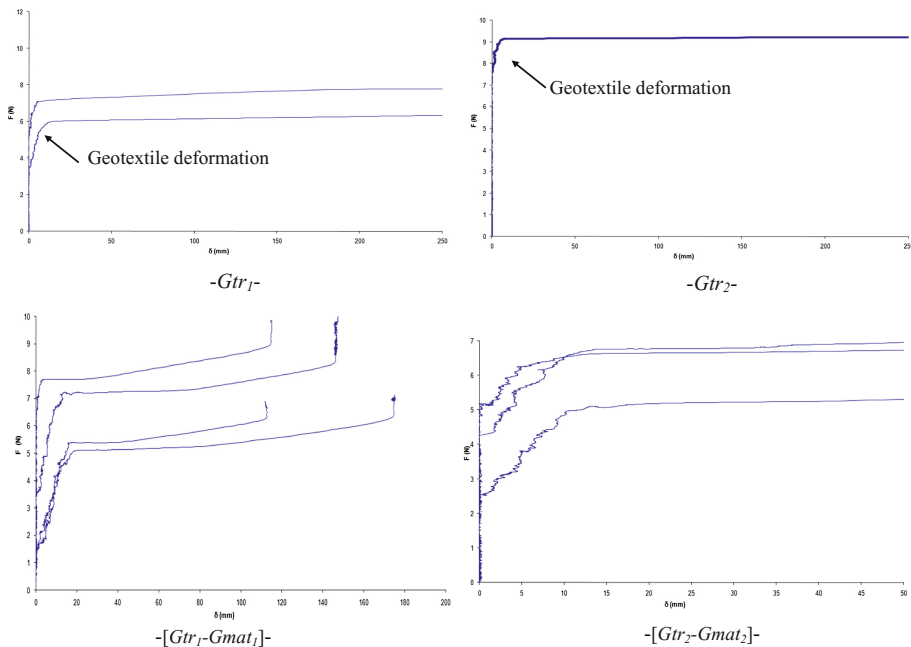
Geosynthetic tension (F^{stat}) mobilized during the static phase ($0 < \beta \leq \beta_0$) are presented in Table 4.

Since all tests were conducted under the same initial normal stress, variation of the geosynthetic tension magnitude was a result of different geosynthetic surface roughness which caused a variation of the mobilized static friction.

Consequently, the two geotextiles Gtr_1 and Gtr_2 presented nearly the same surface roughness since it mobilized the same tension while the geocomposite[Gtr_1-$Gmat_1$]was rougher than [Gtr_2-$Gmat_2$].

During the transitory phase, the deformation of the geotextile Gtr_2 is lower than that of the geotextile Gtr_1 although it mobilized more pseudo-dynamic tension F^{psdyn} (Fig. 12).

These different behaviors were occurred due todifferent mechanical characteristics of the two tested geotextiles since Gtr_2 has a higher tensile modulus (J) than that of Gtr_1(100 kN/m versus 58 kN/m).

Fig. 12. Geosynthetic tension (*F*) versus displacement of the tested geosynthetics.

Table 4. Geosynthetic tension during the static phase.

Geosynthetic of reinforcement	F^{stat} (N)
Gtr₁	8
Gtr₂	9
[Gtr₁-Gmat₁]	6
[Gtr₂-Gmat₂]	4.5

The deformation of the geocomposite [*Gtr₁-Gmat₁*] started earlier than the deformation of [*Gtr₂-Gmat₂*] ($\beta_0 = 12°$ instead $\beta_0 = 16°$). It was a result of higher tensile modulus (*J*) of the geocomposite[*Gtr₂-Gmat₂*] which allowed a longer static phase.

During the dynamic phase ($\beta_0 < \beta \leq \beta_s$), the geocomposite [*Gtr₁-Gmat₁*] continued the deformation caused by a dynamic friction mobilization within the tangled fibers of the geomat. These fibers were loose during the static phase where the tension was mobilized only by the geotextile *Gtr₁*.

However, the behavior of the geocomposite [*Gtr₂-Gmat₂*] was different since its geomat was made of relatively shorter fibers textured on the geotextile *Gtr₂*. This geocomposite exhibited the same tension mobilized during the transitory phase without additional deformation.

Interface friction angles were recalculated by considering the mobilized tensions during the different phases of the inclined plane tests in accordance with the following free-body diagram (Fig. 13).
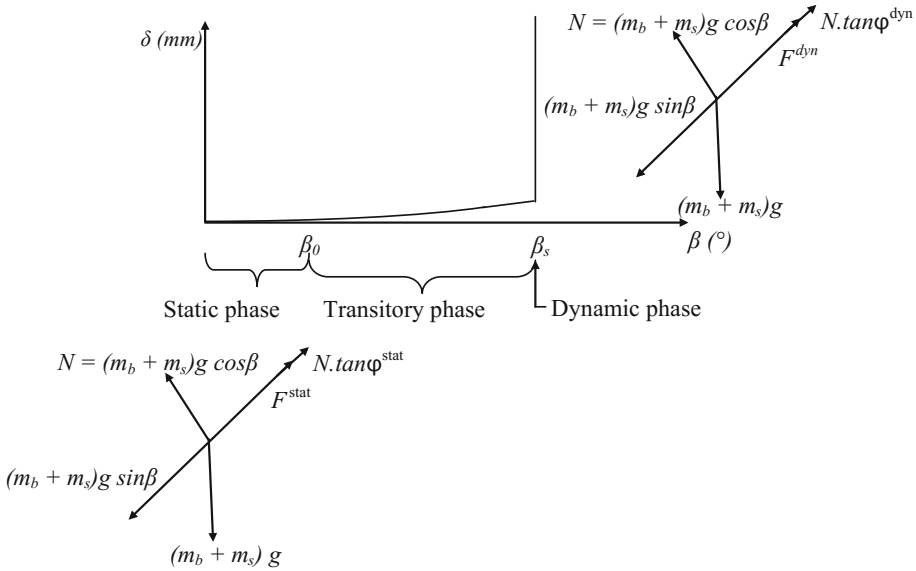
Fig. 13. Free-body diagram of 'Tension Procedure' of the inclined plane test

Table 5 presents the interface friction angles values calculated for the four tested geosynthetics of reinforcement using the following equations:

$$tan\, \varphi^{stat} = \frac{(m_b + m_s) \cdot g \cdot sin\, \beta_0 - F^{stat}}{m_s \cdot g \cdot cos\, \beta_0} \quad (5)$$

$$tan\, \varphi^{dyn} = \frac{(m_b + m_s) \cdot g \cdot sin\, \beta_s - F^{dyn}}{m_s \cdot g \cdot cos\, \beta_s} \quad (6)$$

Rzepecki et al. (2013) performed inclined plane tests on the same geosynthetic products and used the same inclined plane device under two different initial normal stress of 2 kPa and 2.2 kPa with the aim to compare the performance of the different geosynthetic of reinforcement.

Table 5. Soil-geosynthetic interface friction angles calculated in accordance with the "Tension Procedure", the "Static – Dynamic Procedure" and the standard procedure.

«Tension procedure»			«Static- dynamic procedure»		Standard procedure
Geosynthetic of reinforcement	φ^{stat} (°)	φ^{dyn} (°)	φ^{stat} (°)	φ^{dyn} (°)	φ^{stand}
Gtr_1	19	18	20	23,6	26,5
Gtr_2	22	21	23	23,6	25
[Gtr_1-$Gmat_1$]	18	16	19	28,5	32
[Gtr_2-$Gmat_2$]	22.5	21.5	23	29,6	33

Test results were interpreted on the "Static- Dynamic Procedure" of Gourc and Reyes-Ramirez (2004) and allowed the choice of the geocomposite [Gtr_2-$Gmat_2$] as the best geosynthetic of reinforcement among the tested products, similarly to this study results.

The major difference between the "Tension Procedure" and the "static – dynamic procedure" is that the later interprets the gradual sliding by an increase of interface friction with the movement $\left(\varphi^{dyn} > \varphi^{stat}\right)$ as shown on the Table 5.

On the other hand, the «tension procedure» considers the mechanical characteristics of tested geosynthetic which allows a more comprehensive interpretation of the geosynhetic behavior. The diagram geosynthetic tension (F) versus displacement (δ) provides additional information required to correctly understand the sliding mechanism and to assess correctly the interface friction angle.

Best geosynthetic of reinforcement are those mobilizing more the static friction to tension thanks to a better surface roughness and without elongation thanks to a high tensile modulus (J). In this case, more extended static phase is recorded and higher interface friction angle φ^{stat} can be calculated since the used value of β_0 is high.

If geosynthetic deformation is inevitable because of an excessive static friction mobilization under high initial normal stress and good surface roughness conditions, the best geosynthetic of reinforcement is that allowing more elongation allowing a gradual sliding of the retaining soil box on the plane. The relatively extended transitory phase prolongs the time before the inevitable non-stabilized sliding.

6   Conclusions

Inclined plane tests were conducted on two soil-geotextile and two soil-geocomposite interfaces.

Results were interpreted according to the standard method (EN ISO 12957-2), the "static- dynamic procedure" of Gourc and Reyes-Ramirez (2004) and a new procedure which considers the geosynthetic tension when calculating the interface friction angles.

The main advantages of the proposed "tension method" are:

– Provides much suitable information of the geosynthetic behavior during tests and its response in regard to the interface shear strength.
– The calculated interface friction angles seem to be more reliable than those calculated according to the standard and the "static- dynamic procedure" of Gourc and Reyes-Ramirez (2004).

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