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Questions raised regarding interpretation of inclined plane results for geosynthetics interfaces

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ABSTRACT: The inclined plane test is used to determine geosynthetics interface properties, especially in cases where the stress normal to the interface is small. The design of sloped cap covers for landfill sites necessitates this type of test. The parameter usually deduced from this kind of test is the friction angle corresponding to the plane inclination for a relative sliding displacement of 50 mm. In this paper it is showed that this parameter is not relevant and it is demonstrated that considerably greater information could be drawn from this device. The different behaviors, sudden sliding, jerky sliding, gradual sliding, can be justified, combining standard tests with new tests,"dynamic tests" and "abrasion tests". The inclination corresponding to the initialization of sliding, $\beta_0 = \phi_0^{\text{stat}}$ is a relevant parameter as well as ϕ_c^{dyn} dynamic friction angle for constant acceleration $\gamma = \gamma_c$.

1 INTRODUCTION

The design of geosynthetic-based systems used within geotechnical applications, such as geosynthetic liners systems on the slopes of landfill sites, either at the bottom (Feki et al, 2002) or as a cap cover, requires in-depth knowledge of the friction behavior of both soil-geosynthetic and geosynthetic-geosynthetic interfaces. These geosynthetic layers serve one or several purposes, including the following: watertightness (introduced via a geomembrane), transmissivity within the plane (via the presence of a geospacer).The interface between geomembrane (GM) and geospacer (GS) is specifically considered here. These interface relationships are determined using devices of either the shear box or inclined plane type and such equipment is currently undergoing standardization.

2 INCLINED PLANE TEST

2.1 *Adaptation of inclined plane test for dual geosynthetics interface*

For the inclined plane test, the upper box containing conventionally the soil is replaced by a wooden plate on which a 0.7 m long and 0.18 m wide geosynthetic sample has been glued. The initial normal stress $\sigma'_0 = W/S$ is then applied using metal plates as overload (where W, the total weight, included the wooden geosynthetic support plate and S, the area of the interface). The guides on the upper box, which ensure that sliding does not deviate with respect to the slope, are assumed to be frictionless. The lower sample, similar to the soil-geosynthetic tests, is bonded onto the rigid support of the inclined plane (0.80 m × 1.30 m) and fastened at the top. In the standard test, at the beginning the initial state corresponds to an inclination of the base plane ($\beta = 0$), wherein the interface is submitted to an average normal stress σ'_0. The base plane is inclined at a constant rate ($d\beta/dt$ = 3°/min) until obtaining the non-stabilized sliding angle (β_s - continuous sliding at $\beta = \beta_s$ up to the bottom of the Inclined Plane). The effective normal stress acting on the interface decreases during testing ($\sigma' = \sigma'_0 . \cos\beta$). With this set-up, the angle of interface friction ϕ_{gg} is assumed equal to the non-stabilized sliding angle β_s, seeing that guidance of the geosynthetic-containing plate has been assumed frictionless.

The inclined plane (Fig. 1) offers the dual advantage of enabling testing at low normal stresses at the interface and allowing for test condition modulation. However current standards lack sufficient accuracy regarding interpretation of test results (European Standard final draft EN ISO 12957, 2001: Article 2 for the inclined plane test).

Hence, thorough understanding of the complete friction interface relationship (τ/σ' = f (tangential displacement δ, time t) at a fixed normal stress σ'),

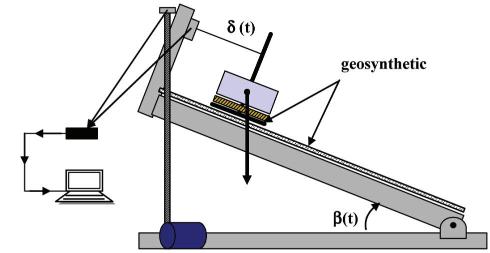


Figure 1. General conditions of the inclined plan test.

and not just of the geosynthetic-geosynthetic friction limit values ($\tau_{limit}/\sigma' = \tan\phi$, ϕ threshold value), is critical to the stability analysis of sloped system. Interface behavior deduced from inclined plane test may be utilized in a more refined manner, while valuable additional information may be drawn from the test, especially during the initial sliding phase.

2.2 *New interpretation of the Inclined Plane Test*

Reyes & Gourc (2003) and Gourc & Reyes (2004) presented a new interpretation and new procedures of test ("dynamic test", "abrasion test" and "creep test"). These protocols are applied in this paper to different interfaces.

In the classical case, the behavior may be separated into three phases (Fig. 2), as follows:

- Phase 1 (static phase): upper box practically immobile ($\delta = 0$) over the inclined plane until reaching an angle $\beta = \beta_0$;
- Phase 2 (transitory phase): for an increasing value of inclination ($\beta > \beta_0$), upper box moving gradually downwards.
- Phase 3 (non-stabilized sliding phase): upper box undergoes non-stabilized sliding at an increasing speed ($d\delta/dt$), even if plane inclination is held constant ($\beta = \beta_s$).

As indicated both in the previous paper (Reyes-Ramírez & Gourc, 2003) and on Figure 3, Phase 2 may be of various types:

– type (a) sudden sliding – abrupt displacement of the upper box under non-stabilized sliding with a nearly-nonexistent Phase 2 ($\beta_0 = \beta_s$);
– type (b) jerky sliding – displacement (δ) increasing in a "stick-slip" fashion;
– type (c) gradual sliding – displacement (δ) progressively increasing with inclination (β).

The non-stabilized sliding (Phase 3) arises very often for plane displacement values of less than the value ($\delta = 50$ mm) conventionally considered when measuring the friction angle (ϕ_{50}^{stat}) (Fig. 3c). From the inclination value $\beta = \beta_s$, the sliding rate of the upper box becomes significant and the mechanical analysis must definitively be conducted using a dynamic approach (taking into account the displacement acceleration γ_c) and not using a static approach as is typical practice. A "static" Phase 1 will thereby be distinguished from a "dynamic" Phase 3, with Phase 2 acting as a transitory phase ($\beta_0 < \beta < \beta_s$) during which the static interpretation is merely an approximation. A constant dynamic friction angle

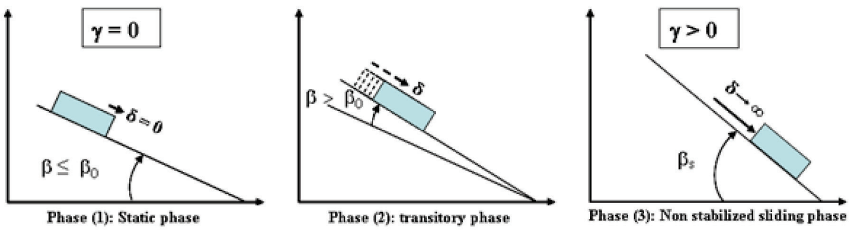


Figure 2. Different phases of upper overloaded plate movement, for increasing inclination of the inclined plane: (a) Phase 1, static phase; (b) Phase 2, transitory phase; (c) Phase 3, non-stabilised sliding phase.

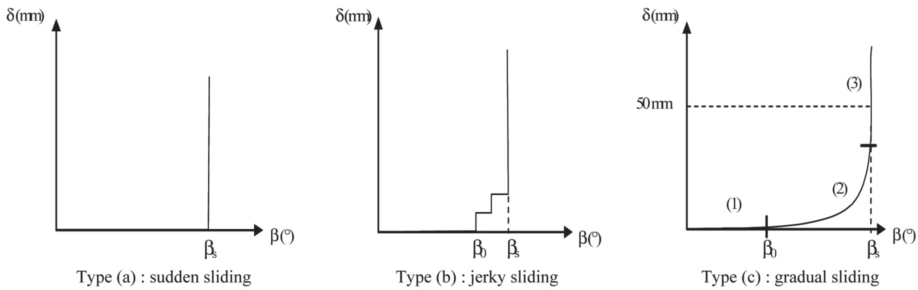


Figure 3. Different mechanisms of sliding observed in the inclined plan test: (a) sudden sliding; (b) jerky sliding; (c) gradual sliding.

(ϕ_c^{dyn}) is found, characterizing the interface friction in a part of the phase (3). It is well-known that for some interfaces (e.g. rock joints and tires for instance), dynamic friction may be entirely different from static friction, due to the influence of the displacement rate (modification of contact conditions) and ultimately the damage (linked to the sliding displacement).

The value of the dynamic angle of friction is obtained from the equation (1) where:

- ϕ_c^{dyn} = dynamic angle of friction for constant acceleration γ_c from a "dynamic" approach
- β_s = inclination for non-stabilised sliding (threshold inclination: $d\delta/d\beta \to \infty$);
- γ_c = constant acceleration (m/s^2); and
- g = acceleration due to gravity (m/s^2).

$$\tan \phi_c^{dyn} = \tan \beta_s - \frac{1}{\cos \beta_s} \cdot \frac{\gamma_c}{g} \quad (1)$$

2.3 *New test procedures*

Three types of tests were performed in the framework of this study:

Standard sliding test:
In agreement with the standard guidelines, the plane is inclined at a constant inclination rate. The tangential displacement δ is monitored versus the inclination β.

The following parameters were assessed during testing:

→ β_s plane inclination corresponding to the non-stabilized sliding;
→ $\beta_0 = \phi_0^{stat}$ static friction angle corresponding to the initialization of the upper box movement;
→ β_{50} plane inclination corresponding to a standard displacement δ = 50 mm;
→ $\beta_{50} = \phi_{50}^{stat}$ standard friction angle

In fact generally the static conditions are no more observed for this displacement. It's better to use the term "pseudo-static conditions":

→ β_s plane inclination corresponding to a large displacement (δ = 800 mm)
→ $\beta_s = \phi_s^{stat}$ pseudo-static limit friction angle.

This value is often used to characterize the friction angle. But disregarding the influence of the acceleration γ (equation 1), this estimation of the friction for large tangential displacement is wrong and should be replaced by ϕ_c^{dyn}:

→ ϕ_c^{dyn} dynamic friction angle for constant $\gamma = \gamma_c$.

ϕ_c^{dyn} is obtained from equation (1) if the acceleration γ is monitored during the dynamic phase of the test (in the conventional procedure, this is not the case).

Dynamic test:
A new kind of test can be performed by holding the box in place without allowing any displacement until reaching an inclination $\beta_{dyn} > \beta_s$ (after conducting a preliminary test to determine β_s) and then suddenly releasing the box. An accelerated movement of the box is directly obtained. The value of ϕ_c^{dyn} is obtained in function of β_{dyn}, following the same equation (1).

Abrasion test
This test consists of testing the same geosynthetic samples several times. For each of the successive tests (numbered j = 1 through n) on the same sample, the upper plate is set into sliding motion beginning at the top (Position "a" on the plane) and stopped after sliding a total of 800 mm. The tangential displacement during a given test, (δ), is denoted in order to differentiate it from the total tangential displacement undergone by the sample (Δ) throughout the series of tests (with (Δ_0) representing cumulative displacement at the start of the test and (Δ_f) the displacement at the end (for Test 1: Δ_0 = 0, Δ_f = 800 mm). β_0, β_{50}, β_s versus the number of tests can be analysed.

3 EXPERIMENTAL PROGRAM

3.1 *Geosynthetics interfaces tested*

For landfills cap liners, a surface water drainage system (geospacer) is generally required. The interface with the geomembrane underneath could be critical.

The present study considers the combination between a geomembrane and a geospacer. Two geospacers corresponding to the same shape concept but of different thickness are associated to two HDPE geomembranes of different superficial appearance (Table 1 and Photo 1). "GS-GM" corresponds to an arrangement where GS is fixed on the upper plate and GM on the inclined plane.

3.2 *Friction characterization of the GMc-GS6 system*

3.2.1 *Standard tests*

On the Fig. 4 we represent the typical diagrams corresponding to the tangential displacement δ versus the inclination β. Every test is repeated one time. The noteworthy result is the significative difference of behaviour when the two geosynthetics are switched ,"sudden sliding" for GM-GS and "gradual sliding" for GS-GM in reference to the Fig. 2. Although surprising, this is confirmed by a more precise analysis. On the lower part of the Fig. 4, this is a zoom for small tangential displacement: for the two different arrangements. The value of $\beta_0 = \phi_0^{stat}$ is logically the same in accordance with the symmetry of the problem. But once sliding process is initiated, the situation is

Table 1. Main characteristics of the geosynthetics used in the tests.

Type of Geosynthetic	Material	Manufacture (notation)	Thickness (mm)
Geomembrane	HDPE	GSE (GMa) Agru (GMc)	1, 5 mm 1, 5 mm
Geospacer	HDPE	Wavin (GS6) Wavin (GS8)	6 mm 8 mm

Photo 1. Geospacers used in the tests.

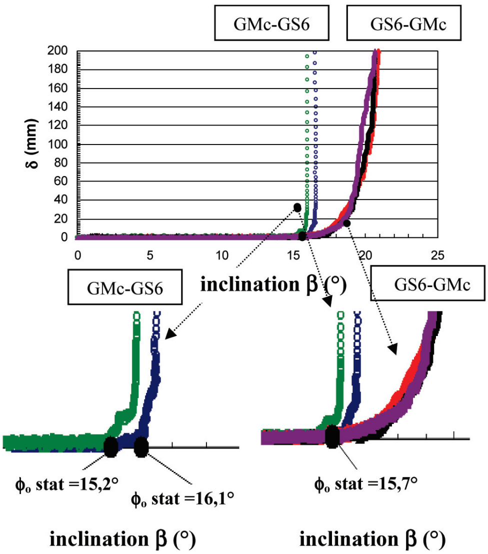


Figure 4. Typical diagrams corresponding to the tangential displacement δ versus the inclination β for an interface between GMc and GS6 when the two geosynthetics are switched.

no more symmetrical since the upper piece of geosynthetic is subjected to a continuous contact with the lower geosynthetic unlike the lower one.

3.2.2 *Dynamic tests*

Achieving process for acceleration γ_c is displayed on the Fig. 5: it could be observed that in every case the movement is becoming uniformly accelerated. The constant slope of the diagram of the displacement rate versus time corresponds to a constant acceleration. The numerical results are included in the Table 2.

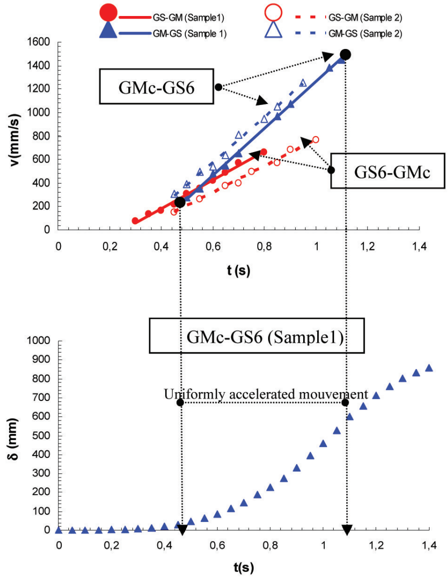


Figure 5. Dynamic tests: process for determining acceleration γ_c on GM-GS system.

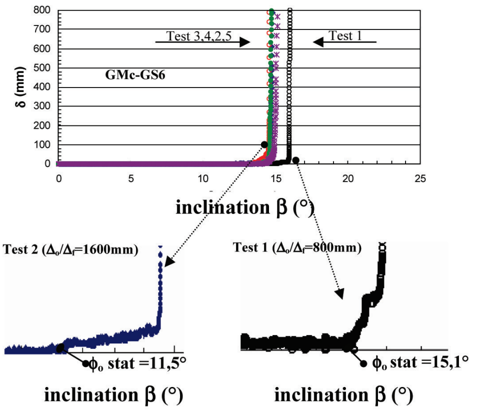
Table 2. Results of dynamic tests on GM-GS system.

	Interface GMc-GS6		
	Sample 1		Sample 2
β dyn (°)	25.1		25.1
γ_c (m/s^2)	1.9956		1.9071
ϕ dyn (°)	13.7		14.2
ϕ dyn average (°)		13.9	
ϕ_o stat average (°)		15.65°	
	Interface GS6-GMc		
	Sample 1		Sample 2
β dyn (°)	25.2		25.2
γ_c (m/s^2)	1.2160		1.1273
ϕ dyn (°)	18.4		18.9
ϕ dyn average (°)		18.7	
ϕ_o stat average (°)		15.7°	

It was suggested (Gourc & Reyes 2004) that "sudden sliding" (GM-GS) corresponds to $\phi_c^{dyn} < \phi_0^{stat}$ and "gradual sliding" (GS-GM) corresponds to $> \phi_c^{dyn} < \phi_0^{stat}$. This is confirmed by the results of the Table 2, considering that $\phi_0^{stat} = 15.5°$.

3.2.3 *Abrasion tests*

So the results of standard tests and dynamic tests are consistent but one question is pending: why the value of ϕ_c^{dyn} is different for the two arrangements? A



Test(i)	1	2	3	4	5
Δ_o/Δ_f (mm/mm)	0/800	800/1600	1600/2400	2400/3200	3200/4000
$(\phi_o \text{ stat})_i$ (°)	15.10	11.50	13.50	13.87	13.80
$(\phi_{50})_i$ (°)	15.95	14.60	14.39	14.60	14.81

Figure 6. Abrasion tests performed on GM-GS system (5 successive tests on the same sample).

possible reason is the alteration of friction with the relative tangential displacement.

On the Fig. 6 successive friction tests (j = 1 to 5) are performed on GM-GS system using the same sample of geomembrane in contact for every test with a virgin geospacer: after the first test, $(\phi_0^{stat})_j$ is decreasing and remains constant for the following tests. So it can be assumed that damage of the geomembrane due to the continuous sliding displacement induces a decrease of the friction angle. This trend is compatible with the dynamic tests since $\phi_c^{dyn} < \phi_0^{stat}$.

3.3 *Friction characterization of the GMa-GS8 system*

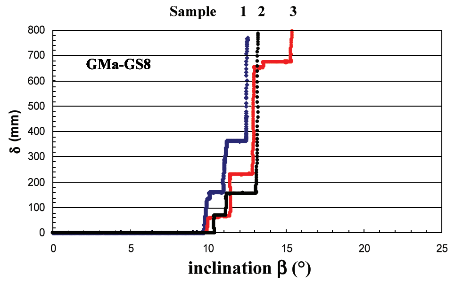
In order to confirm the general character of the results above, another system is considered, with a thicker geospacer (GS8) associated to another geombrane (GMc).

3.3.1 *Standard tests*

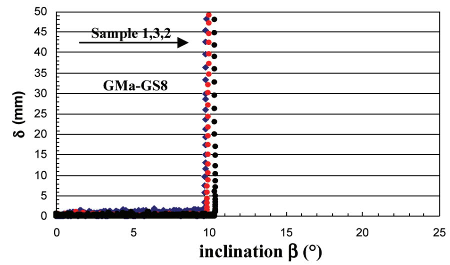
On the Fig. 7, three different samples (virgin GM associated to a virgin GS) are tested. The diagrams (b) until a displacement δ = 50 mm are very closed and correspond to a "sudden sliding". On the other hand, a typical stick-slip phenomenon ("jerky sliding") is observed beyond this displacement (figure (a)).

3.3.2 *Abrasion tests*

On sample 3 of the Fig. 7, abrasion tests are performed (Fig. 8). Stick slip phenomenon disappears after the first friction test, for j = n2 to 5 and the initial friction angle $(\phi_0^{stat})_j$ at the beginning of every successive test (j) is practically constant.

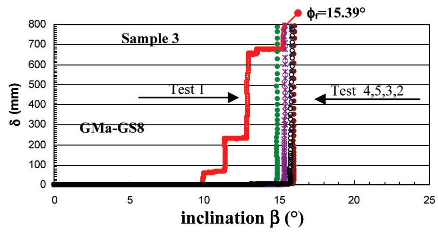


(a)



(b)

Figure 7. Standard friction test (repeated 3 times) on the GMa-GS8 system: (a) global curve until δ(b) zoom on the phase δ < 50 mm.



Test(i)	1	2	3	4	5
Δ_o/Δ_f (mm/mm)	0/800	800/1600	1600/2400	2400/3200	3200/4000
$(\phi_o \text{ stat})_i$ (°)	9.85	12.49	15.00	15.26	14.03
$(\phi_{50})_i$ (°)	9.98	14.88	15.37	16.00	15.70

Figure 8. Abrasion tests for the GMa-GS8 system (5 successive friction tests on the same sample).

Stick slip phenomenon could be attributed to specific surface condition of the virgin geosynthetics. As demonstrated by the standards tests beyond δ = 50 mm and abrasion tests, the $\beta_{50} = \phi_{50}^{stat}$ standard value corresponding to δ = 50 mm is not a significative value for design, since in the field operation on geosynthetics unrolling will induce large relative tangential displacements at the interface between geosynthetics.

4 CONCLUSIONS

Sliding mechanisms on actual slopes of cap liners are undoubtedly well modelled by an inclined plane test. However as demonstrated above, the conventional interpretation of the test (Standard EN-ISO 12957-2), taking into account the observed inclination for δ = 50 mm is not relevant and often not conservative. It would be reasonable to revisit the corresponding ISO-CEN Standard.

For the geosynthetic-geosynthetic interface, the decision to select either ϕ_0^{stat} or ϕ_c^{dyn} for design of geosynthetic systems on slopes will be dependent on the expected field of application.

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