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Influence of hydraulic conditions on the stability of geosynthetic systems on slopes

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ABSTRACT: Systems comprising geosynthetics constitute a preferential slip line when they are laid down on the slopes of civil engineering structures and their stability must be checked with care. With this objective in mind, as well as that of improving the characterisation of friction at geosynthetic interfaces and therefore the calculation of the dimensions of such systems on slopes, an apparatus of the “inclined plane” type was designed. Two full-scale experiments validated the many results obtained with this apparatus and, in particular, highlighted the influence of wetting of the materials on friction angles and confirmed the influence of saturation of the protective soil cover on the stability of geosynthetic systems. In parallel with these experiments, using existing calculation methods and integrating the hypotheses concerning the application of the various hydraulic conditions validated by our experiments, a geosynthetic system slope stability calculation software programme was developed.

1 INTRODUCTION

Systems comprising geosynthetics are widely used in civil engineering structures such as hydraulic structures and landfills etc. They offer the particular advantage of being easy to install compared with traditional solutions and provide an interesting alternative from the economic point of view.

These systems (Figure 1) are composed of a geosynthetic complex comprising one or several layers of geosynthetics with layers of granular soil above and below it. These systems have one or several functions among which we could mention, for example, that of a barrier when the geosynthetic system includes a geomembrane, or drainage when it includes a drainage geocomposite.

Figure 1. Installation of a geosynthetic system on the face of a dam

Geosynthetic systems often pose problems of stability when they are laid down on the slopes of structures. In fact, the preferential slip line is generally located inside the geosynthetic complex where the friction angles between the materials composing it are generally low, notably in contact with geomembranes. It is therefore important to calculate the dimensions of such systems in the light of this, so as to avoid any instability during their installation or in the course of the lifetime of the structure. The normal stress applied to such geosynthetic complexes on slopes is usually low (<10kPa) and is essentially due to the weight of the protective soil cover and to the movements of machinery during installation. These systems may also be subject to various hydraulic conditions that can have a negative effect on their stability.

This article is part of a study into the stability of geosynthetic systems on slopes. Further to a bibliographical review covering, on the one hand, different stability calculations and, on the other, various experimental feedback (failures, full-scale experiments), it appeared that the calculation of the stability of geosynthetic systems on slopes required an improvement in the characterisation, under low normal stress, of the friction between the various materials composing them, as well as the inclusion of the hydraulic conditions applied to the systems. In order to achieve these two objectives, we developed specific tools (test apparatus and stability calculation software) and carried out the full-scale experiments presented in detail in this article.

2 BACKGROUND

2.1 *Calculation Methods*

The analysis of geosynthetic system stability on slopes has been the subject of many approaches. Among these, the analytical methods of Giroud and Beech (1989) and of Koerner and Hwu (1991), called two-wedge methods, are very widely used. These methods consist in studying the static equilibrium of two wedges, one active and one passive, and in resolving the equations obtained by adopting some hypotheses on the unknowns. The difference between the methods of Giroud and Koerner resides essentially in the determination of the geometry of the active wedge and in the definition of the safety factor in the Koerner method.

The inclusion of hydraulic conditions has also been studied by these authors (Soong and Koerner, 1996; Giroud et al., 1995). The different calculations under hydraulic conditions were made working on the hypothesis of seepage parallel to the slope (Figure 2.a) and highlighted a significant reduction in stability (safety factor divided approximately by 2) when the protective soil cover was completely saturated. This reduction shows the influence of seepage on the stability of geosynthetic systems on a slope, as well as the necessity of taking this into account when designing such systems by installing, for example, a drainage system between the geomembrane and the protective soil cover.

Poulain et al. (2000) adapted the two-wedge method, taking into account hydraulic conditions, to cases involving geosynthetic liner systems installed on canal banks. This calculation method proposed to determine the safety factor and the anchor force to be taken up at the top of the slope when stability was not ensured. It was presented for three canal configurations: canal not in use, canal in service at its normal navigation level and passing of a boat generating a rapid drop in water level.

In the case of a canal in service at its normal navigation level, the weight per unit of volume of the soil located under the water level (Figure 2.b) is considered. In the case of the rapid drop in the water level on passage of a boat (Figure 2.c), the main difference in relation to the calculation method put forward by Soong and Koerner (1996) resides in the taking into account of the direction of the seepage flow lines in the protective soil cover: the flow lines are presumed to be horizontal in the part of the protective soil corresponding to the height h_2 of the drop in the water level (worst-case configuration).

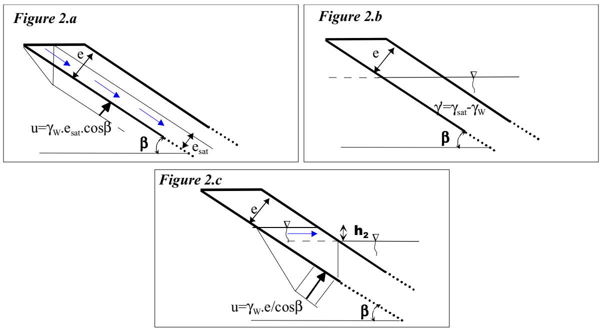

Figure 2. Examples taking hydraulic conditions into account.

It should be noted that for the different calculation methods proposed, no hypothesis has been made concerning the direct influence of water on the friction angle between the various components of the geosynthetic system.

As far as we know, few full-scale experiments or laboratory tests have been performed to check the influence of water on the stability of the geosynthetic system and thus to validate the hypotheses taken into account by the various existing calculation methods.

2.2 *Experimental feedback*

It is often on the basis of cases of failures that highly detailed studies of geosynthetic system stability have been carried out and that calculation methods have been developed (Seed et al., 1990). The case of the slipping of the geosynthetic system on the Aubrac dam (Girard et al., 1990) is precisely one of the reasons behind our study. The various local and global approaches developed and the methods of determining the characteristics required for the calculations are generally validated via *in situ* experiments (Thomas, 2000). These experiments enable a better understanding of friction mechanisms and allow us to put forward methods for calculating the necessary dimensions for actual structures.

2.3 *Orientation of our Study*

In the framework of our study, we propose to develop testing apparatus and to carry out full-scale experiments to enable us to characterize the geosynthetic interface friction in various hydraulic conditions and to check the influence of water on stability so as to validate the various existing calculation methods.

3 CHARACTERIZATION OF FRICTION USING AN INCLINED PLANE

The new inclined plane (Briançon, 2001) developed at the Cemagref meets the French and the projected European test standards. As well as this, this inclined plane allows tests to be carried out reproducing the different possible effects of water. In fact, it can be set up with watertight walls and a specific system to wet the geosynthetic, generate seepage in the protective soil cover and simulate filling or rapid emptying.

3.1 *Development of new procedures*

The test described by the standards poses problems of interpretation for certain geosynthetic interfaces, in particular when the slipping is gradual. We developed a first test procedure (Briançon, 2001) allowing better characterization of the interface being tested by measuring the stress generated in the geosynthetics being tested. This procedure made it possible to determine the moment when slipping begins more precisely. The tests carried out under hydraulic conditions required to develop a second procedure (Briançon, 2001); in this case, it was the force required to hold back the upper box that was measured.

3.2 *Main Results*

A large number of interfaces were tested in dry conditions in order to validate the new procedures. The tests with wetting of the geosynthetic interface highlighted a reduction in the friction angle - a decrease that was larger or smaller depending on the interfaces. A wet friction angle was then defined to take this effect into account. The tests with seepage in the protective soil cover confirmed the influence of the uplift generated by this seepage on the stability of the geosynthetic system; the reduction in the resisting force due to this uplift was highly significant, and must be taken into account when designing geosynthetic systems for slopes.

4 FULL-SCALE VALIDATION

4.1 *Influence of the wetting of the materials*

The influence of the wetting of the materials highlighted by the inclined plane tests was subjected to full-scale validation. This validation consisted in performing an experiment *in situ* on the slopes of a basin alongside a motorway.

Figure 3. Laying down the protective soil cover on the slopes of a motorway basin

Two test plots (Figure 3) were laid out on a slope 10 metres in length and inclined at an angle of 20°. Each test plot comprised both a reinforcement geocomposite GTX_R and a geomembrane (a polypropylene geomembrane GMB_{PP} for test plot 1 and a bituminous geomembrane $GMB_{B(L)}$ – smooth side of the geomembrane towards the geotextile – for test plot 2)). The protective soil cover was laid down to a thickness of 0.25m using a hydraulic excavator.

Analysis of the different measurements taken on site showed that no effort induced by the laying down of the protective soil cover was transmitted to the geomembranes. The friction angles were calculated on the basis of the tensions generated in the geotextiles and the weight of the soil cover in the absence of an abutment. Table 1 presents the calculated friction angle values for the two test plots and the measured angle values for the two interfaces in question. The calculation is made from the relation (1) below with $U_H = 0$ and $U_N = 0$. It will be noted that the calculated values correspond to the measured values in wet conditions; this observation confirms the validity of the *in situ* experiments which were carried out in the rain and thus in wet conditions for the interfaces

Table 1. Friction angles measured on the inclined plane and calculated on the basis of the experiment.

	Inclined plane		*In-situ* experiment
	Dry conditions (δ)	Wetting of the interface (δ_H)	
δ "GTXR / GMBPP"	16.5°±1°	15°±1°	15°
δ "GTXR / GMBB(L)"	23.5°±1°	18°±1°	18°

4.2 *Demonstration of the influence of saturation of the protective soil cover on stability*

A second full-scale experiment was carried out to check the influence of the saturation of the upper soil on the stability of a geosynthetic liner system. This experiment was performed on a short slope (L=4m) inclined at an angle β=22°. The geosynthetic system was installed in such a way that, when applying the hydraulic conditions, the water was channelled through the protective soil cover of the geosynthetic system without any lateral leakage. The protective soil cover was loaded onto the slope by hand, starting at the bottom, in eight sections with thickness of 0.25 m (Figure 4). The geosynthetic complex was identical to that used in test plot 1 of the experiment presented above.

Figure 4. Installation of the protective soil cover in the second experiment.

During loading, no effort was transmitted by the geomembrane at the top of the slope. The efforts transmitted by the geotextile were measured during loading and over the six hours after loading had been finished. These measurements indicated that there was a significant release of the tension in the geotextile at the top of the slope over the six hours following the end of loading, of about 25% of the maximum tension.

The comparison between the tension Ti_{mes} measured in the geotextile at the end of each stage i of loading the protective soil cover and over the following six hours, and the calculated tension Ti_{calc} worked out on the basis of the friction angle measured on the inclined plane (δ=16°) draws the following remarks (Figure 5):

- for the first three stages of loading, there was full mobilisation of the friction: $Ti_{mes}=Ti_{calc}$;
- for the next five stages: $Ti_{mes}>Ti_{calc}$, the friction was not entirely mobilised at the geosynthetic interface;
- six hours after the end of loading, $Ti_{mes}=Ti_{calc}$, the whole of the system had been freely deformed under the weight of the soil cover and the friction at the geosynthetic interface was fully mobilised.

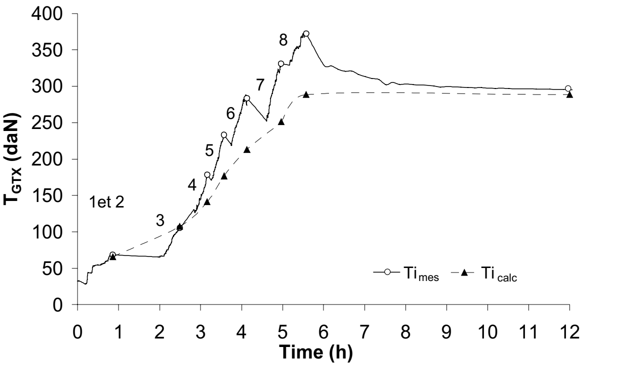

Figure 5. Tensions in the geotextile

The friction angle at the geosynthetic interface measured on the inclined plane was therefore validated by this first phase of the experiment, the phase in dry conditions. A certain length of time was necessary at the end of installation for the friction to be fully mobilised, something that was not observed in the first experiment; the dynamic effect generated by the hydraulic excavator on the relative displacements of the geosynthetics in the first experiment may explain this difference.

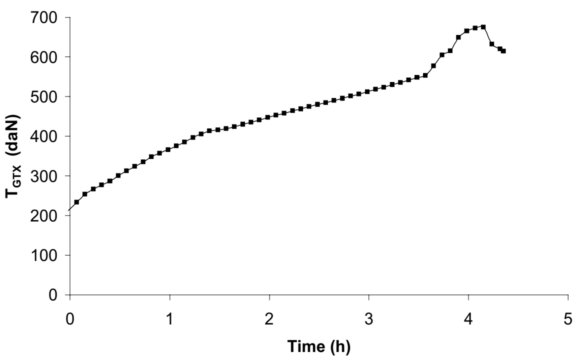

Figure 6. Tension at the end of the geotextile during saturation of the protective soil cover

The soil cover was saturated by watering and by maintaining a constant water level at the top of the slope for more than 4 hours. In the course of this test, the measurements of the stresses at the end of the geotextile and the geomembrane, and the measurements of the water pressure at the base of the soil cover were taken (Figure 6). As when loading the soil, a stress of zero was observed at the end of the geomembrane. The changes in the angle of the curve showing the tension T_{GTX} over time were linked to the irregularities in the application of the hydraulic conditions. The thickness of the saturated soil cover was determined on the basis of measurements provided by a pressure sensor installed in the bottom third of the slope and by seven piezometers placed at regular intervals down the slope; this thickness was equal to 21 cm at the end of the test.

To examine the influence of the saturation of the protective soil cover on the stability of the geosynthetic system, we proposed to calculate the thickness of saturated soil in the protective soil cover corresponding to the tension at the top of the geotextile measured at the end of the test. The measurements of the piezometers and the pressure sensor indicated that the thickness of saturated soil was parallel to the slope at the end of the test.

The balance of the forces (Figure 7) applied to the geotextile and projected parallel to the failure surface gave:

$$W_S.\sin\beta + U_H = \left(W_S.\cos\beta - U_N\right)\tan\delta + T_{GTX} \qquad (1)$$

with W_S: weight of the soil cover,
U_H: pressure of the water upstream,
U_N: resultant of the water pressure applied on the interface,
T_{GTX}: stress at the top of the geotextile.

To resolve equation (1), it was necessary to determine W_S, U_H and U_N in relation to the geographical parameters of the problem and the thickness of saturated soil e_{sat}. As seepage was presumed to be parallel to the slope at the end of the test, the water pressure applied to the interface was equal to $\gamma_w e_{sat}\cos\beta$. Using equation (1), the thickness of saturated soil corresponding to stress at the top of the geotextile equal to the maximum value measured at the end of the test, just before the soil cover slid down the geotextile, was calculated. This saturation thickness was 18cm, calculated on the basis of a friction angle equal to 16°. It was equal to 17cm working on the hypothesis of the influence of wetting of the interface on the value of the friction angle that was then equal to 15° in this case.

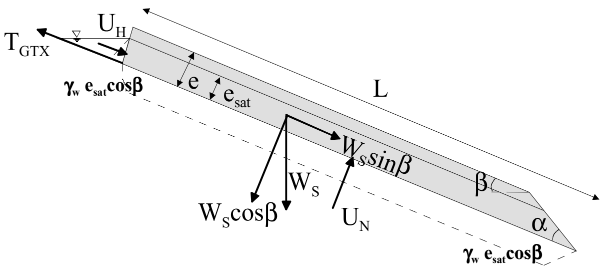

Figure 7. Forces applied to the geotextile in the course of the saturation of the protective soil cover

This calculated thickness of saturated soil was slightly lower than the value determined on the basis of the measurements supplied by the piezometers and the pressure sensors; two hypotheses can be put forward to explain this slight difference:

- as the soil was not evenly saturated, the accuracy of the experimental determination of the thickness of saturated soil can be evaluated as being ±2cm ;
- the soil cover may have slipped slightly creating an abutment; in these conditions, the stress measured at the top of the slope may have been underestimated at the end of the test.

In the course of the saturation of the soil cover, the stresses measured in the geotextile and the slipping of the protective soil cover highlighted the importance of the role of the hydraulic conditions and, notably, of the uplift generated at the geosynthetic interfaces. The results of this experiment confirm the choice of the different hypotheses proposed to calculate the stability of geosynthetic systems on slopes taking hydraulic conditions into account.

5 DEVELOPMENT OF CALCULATION SOFTWARE

Continuing in our study, we developed a software programme based on the principle of the two-wedge method with the introduction of a safety factor and the inclusion of hydraulic conditions: saturation of the protective soil cover, modelling of a rapid drop in water level and constant water level. This software takes into account the hypotheses put forward by Poulain et al. (2000) in the case of a rapid drop in a water table. It provides data-entry assistance, in particular in relation to the geometry of the slope, the composition of the geosynthetic system and the hydraulic conditions applied. The protective soil cover may be of constant or variable thickness. The safety factor is determined for the interface with the lowest friction angle. When the system is not self-stable, the force to be taken up at the top of the slope is calculated for a safety factor set by the user.

6 CONCLUSION AND ACKNOWLEDGMENTS

In order to improve characterization of the friction at geosynthetic interfaces, a new apparatus of the inclined plane type was designed. Different types of tests under hydraulic conditions could thus be developed. The tests carried out with wetting of the geosynthetic interface highlighted a reduction in the friction angle that varied depending on the type of interface being tested. The tests with saturation of the soil cover showed the influence of the uplift generated by this seepage on the stability of the geosynthetic system.

The results of the inclined plane tests were validated by two full-scale experiments. These experiments confirmed the major role played by the wetting of the geosynthetic interfaces and the saturation of the protective soils cover on the stability of the geosynthetic system.

On the basis of the results obtained in these various experiments, we developed a software programme for calculating stability of geosynthetic systems on slopes. The use of these new tools (inclined plane and calculation software) that take hydraulic conditions into account enables a global approach to problems of geosynthetic system stability on slopes.

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