PULL-OUT TESTS ANALYTICAL MODELLING TO DEDUCE THE CONSTITUTIVE SOIL/ REINFORCEMENT INTERFACE BEHAVIOUR

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Abstract: In the field of soils reinforcement, the analytical or numerical modelling with classical friction models, used for metallic reinforcements, does not permit the reproduction of the actual behaviour of synthetic reinforcements due to their extensibility. However, using a modified tensile-strain model makes it possible to simulate the elongation of the synthetic straps and their delayed mobilization. To check the validity of this modified analytical model, several pull-out tests were carried out in a three-dimensional physical model.

Keywords: reinforced earth structure, geosynthetic, physical modelling, pull-out test, interface friction, tensile strain, tensile strength.

INTRODUCTION

Reinforced earth civil engineering methods use strips horizontally embedded in layers of soil to grip strongly enough to enable the construction of high vertical banking, large embankments or abutments. Commonly, geosynthetic strips, which can exhibit relatively large elongation in service, are used in aggressive environments. This reinforcement system constitutes a complex soil/structure interaction problem.

The behaviour modelling of the geosynthetic reinforcement anchored in the ground requires a complex friction model. Several parameters have then to be taken into account, which directly relate to the extensible reinforcement behaviour or its interaction with the soil mass. The main parameters relating directly to the reinforcement, concern its elongation. However, most of the friction models used in design of synthetic reinforced structures are based on a linear elastic strap behaviour. The reality is more complex and the elongation modulus of the geosynthetic can be obtained by a nonlinear function. The second parameter that is necessary to take into account in the tensile-strain model relates to the confinement stress level. Indeed, the elongation modulus of the geosynthetic is also a nonlinear function of the confinement stress level (Ling et al. 1992). Wu (1991) presented a determination method of the geosynthetic elongation modulus according to the confinement stress conditions and with Ballegeer & Wu (1993) different values of geosynthetics stiffness.

The parameters concerning the interaction between the soil and the reinforcement, which are necessary to take into account, relate to the progressive mobilization of the strap. This progressive mobilisation was highlighted by several authors for various types of reinforcement. Mohan & Kumar (1963) and Cambefort (1964) in the piles friction, Alimi et al (1977) in pull-out tests of metallic reinforcements and Bourdeau & Wu (1990) in the pull-out tests of geotextile reinforcement. This phenomenon is more important in the case of the synthetic reinforcement due to their extensibility. However, most of the usual friction models used in the structurural design reinforced by this type of reinforcement, are based on a bilinear friction law of Cambefort's type (1964) or three-linear of Frank and Zhao's type (1982). These assumptions do not take into account the progressive mobilization of the reinforcement. Plumelle (1979) introduced a hyperbolic local friction law to model this phenomenon. Schlosser (1981), Segrestin and Bastick (1996) modelled the progressive mobilization starting from classical of friction and tensile-strain model with considering that the reinforcement mobilization is done in three successive stages. Bourdeau & Wu (1990) shows that the displacements mobilization along a flexible reinforcement is progressively increasing if it is not plane; he proposes as Schlosser (1981), a behaviour model with three successive stages considering a modified tensile-strain law which includes at the beginning an ε_0 to take into account the initial strain of the inclusion before any tensile load application.

In this paper we present, in the first part, the pull-out tests carried out on extensible reinforcement various confinement stress levels. Then, in the second part, we present an analytical method based on a modified tensile-strain law to model the delayed extension mechanism of synthetic reinforcements (Bourdeau & Wu 1990). Finally, the modelling of experimental results by two analytical methods, the first one based on the modified tensile-strain model and the second based on classical models.

NOTATION

L :reinforcement length (m)
L* :length of reinforcement embedded in resistance zone (m)
T_T :head tensile force
U :local displacement
U_T :head displacement
Ux :displacement at x point.
dx :infinitesimal element length along soil-reinforcement interface (m)
k_0 :Vertical and horizontal stress ratio

p :reinforcement perimeter (m)
σv :vertical stress applied on the reinforcement (kPa)
γ :bulk unit weight (N/m3)
τ :interface shear stress (N/m2)
τ* :maximum of soil/reinforcement interface shear stress (N/m2)
J :geosynthetic elongation modulus (N/m)
ε :local deformation
ε_0 :initial deformation threshold

EXPERIMENTAL TESTS

Several laboratory pull-out tests were carried out on synthetic reinforcement developed by *Terre Armee International®* and used in soil reinforcement. These tests allowed the deduction of the behaviour of the synthetic reinforcement and especially to define the interaction parameters between the soil mass and the reinforcement. They were carried out in a test tank of $2m^3$ filled of dense sand (Figure 1) using a pluviation device. The strip was anchored in the sand at the centre of the tank and an airbag placed between the top of sand and the cover plate permits to apply a surcharge to allow simulation of vertical stresses applied at various depths of a real earth reinforced structure. The pressure applied was controlled by two sensors; a pressure gauge making it possible to measure the pressure applied in the airbag and a total pressure sensor installed at the bottom of the tank monitoring the actual vertical stress applied. A total pressure sensor was also installed on the wall of the tank to measure the horizontal stress.

To follow the strap behaviour in the tank, it was instrumented by displacement sensors along its entire length and by a force sensor at its head (Figure 1 and 2).

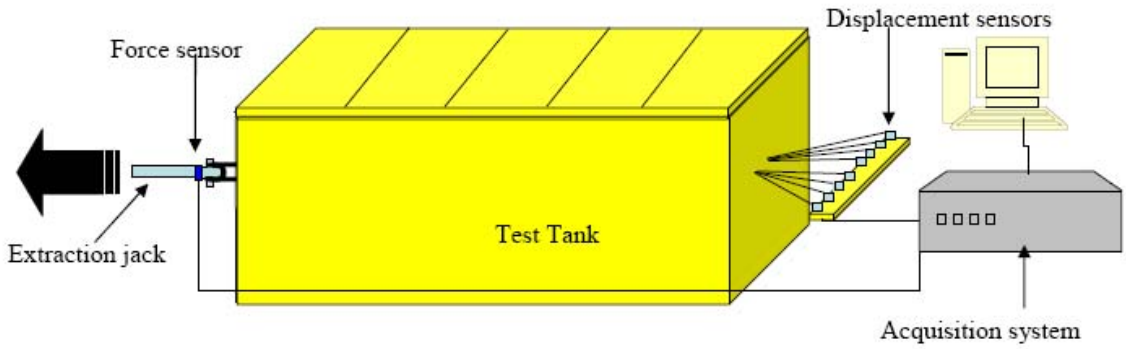

Figure 1. Pull-out test rig

The test reinforcement (Geostraps) were made of geosynthetic strips containing high-tenacity polyester yarns protected by a low density polyethylene sheath. The dimensions of these strips were: 50 mm width, 2 mm thickness and the two strips were set up in two parallel parts spaced by 50 mm (Figure 2). Terre Armée Internationale® makes use of this system to remove any metallic intermediary (thus corrodible) between the concrete facing and the reinforcement strips in the reinforced earth structures. The soil used in the tests was fine sand (0.16-0.63mm) known under the name of Hostun RF. Its density varied between 1.32 - 1.59 and its friction angle was 38° (Gay 2000; Gaudin et al, 2002). The set-up of the soil was carried out with a technique of granular sample reconstitution by material discharge in order to control its density and to simulate the reconstitution of a sandy ground formed by sedimentation.

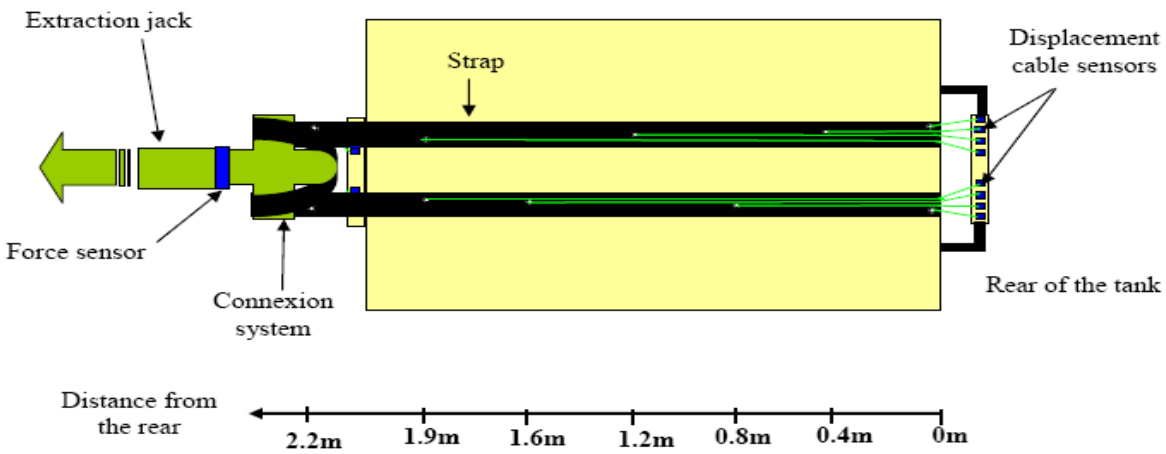

Figure 2. Geostrap and sensors positioning

ANALYSIS OF TESTS RESULTS

The installation of various sensors in the test tank permited not only the analysis of the strip behaviour but also the study the influence of various parameters and test conditions on the reinforcement. Figure 3 shows that the ratio of horizontal over vertical stresses (k0) increases as the vertical stress increases. This result is related to the friction increasing on the tank walls and arching which defers a part of the load on the tank sides. Indeed, the stress measured at the bottom of the tank is lower than that actually applied. This reduction becomes more important as the pressure increases. So, horizontal stress will be more significant when the vertical stress increases.

The material density greatly influenced the friction at the soil/reinforcement interface. Figure 4 shows that, for a confinement stress of 100 kPa, the maximum friction coefficient at the soil/reinforcement interface decreased from 0.79, for a Unit Weight of 15.4 kN/m^3 to 0.6 for a Unit Weight of 14.1 kN/m^3. The best values of friction coefficient corresponded to a density higher than 1.5Te/m^3 for the dense sand used in the tests.

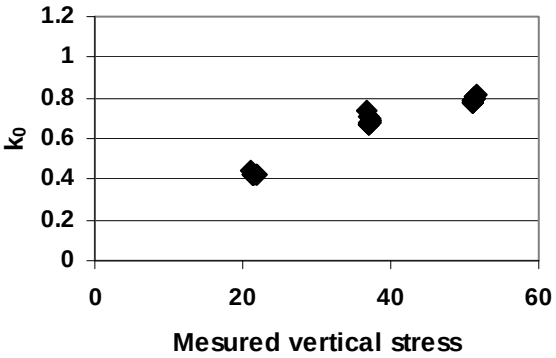

Figure 3. k0 parameter versus measured confinement stress

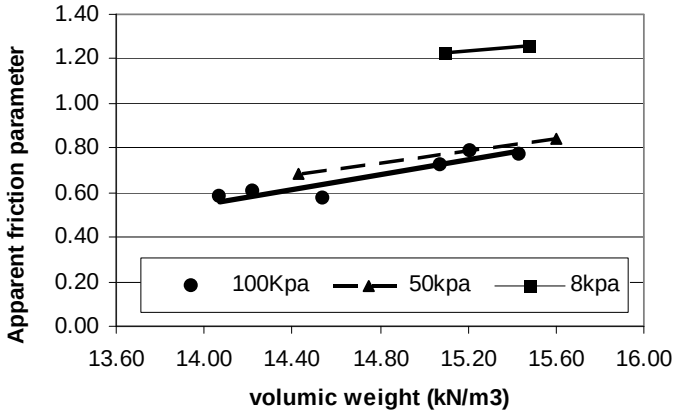

Figure 4. Maximum apparent friction parameter versus volumic weight

The results of various tests show that the behaviour of the synthetic reinforcement is highly influenced by the confining stress. In fact, when this is low, the strip behaves as a stiff reinforcement and presents an elasto-plastic behaviour (Figure 5) and its distal end is mobilized after a small displacement of the head. However, when the confining stress is significant, the reinforcement first starts to move slowly at the head, this stage corresponds to the beginning of the frictional mobilization along the strip (first slope of the curve, figure 5). Then, the displacement increases when the friction is fully mobilised on a section of the strip (second slope of the curve, figure 5). Finally, when the friction is fully mobilised over the entire strip, it behaves as a stiff reinforcement. Figure 6 shows that the reinforcement at the rear only moves after a large displacement (50mm) at the head due to its elongation behaviour.

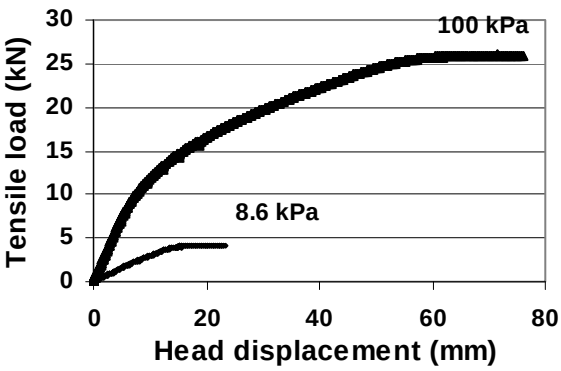

Figure 5. Strip behaviour at the head under different confinement stresses.

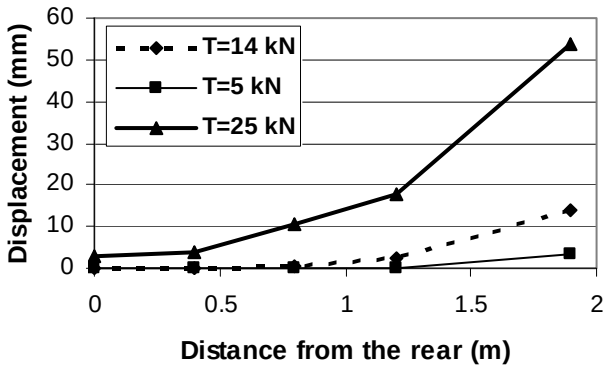

Figure 6. Mobilized strip length under different applied tensile-load (confinement stresses= 100 kPa)

Figure 7, which presents the displacement along the strip for an applied tensile load of 5 kN, shows that the tests carried out under confining stress of 100 kPa mobilized 0.7m of strip length. However, for the test carried out under a confinement stress of 25 kPa, for the same tensile-load (5 kN) it mobilized 1.5 m of the strip length. Until now, this phenomenon has not been taken into account in frictional models, as it was believed the strain affects the entire strip at the beginning of tensile-load application.

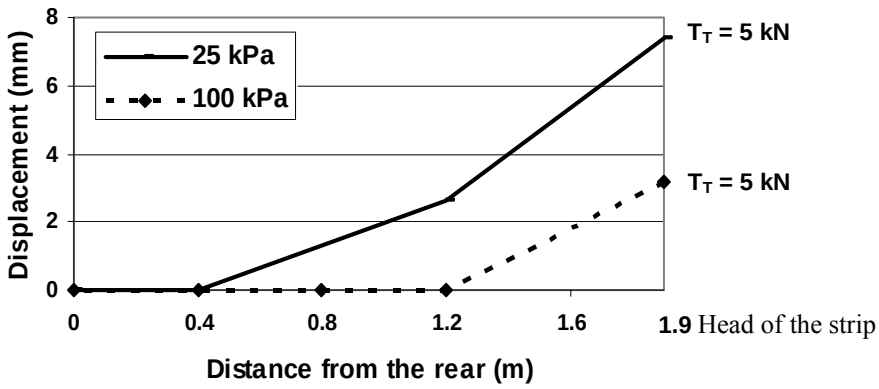

Figure 7. Mobilized strip length under tow different confinement stresses (25 and 100 kPa)

ANALYTICAL DESCRIPTION OF THE DELAYED EXTENSION MECHANISM STARTING FROM THE MODIFIED TENSILE-STRAIN MODEL

Combination of the tensile-strain law T - τ of the inclusion and the local friction law τ - U allows consideration of the progressive friction mobilization on the ground-inclusion interface, permitting the determination of the anchorage law of the extensible reinforcement. In fact, to take into account the delayed extension mechanism, the tensile-strain law is modified and includes an ε_0 at the origin which corresponds to an initial threshold strain (Bourdeau et al. 1990, Figure 8). However, the friction model will be a Cambefort type (Figure 9). The limiting friction τ*, the displacement U* and the slope, k, represent the parameters allowing the characterization of this behaviour model. The parameters of this law are: the tensile-strain T, the deformation ε and inclusions elongation modulus J.

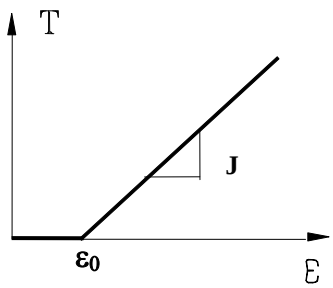

Figure 8. Tensile-Strain model

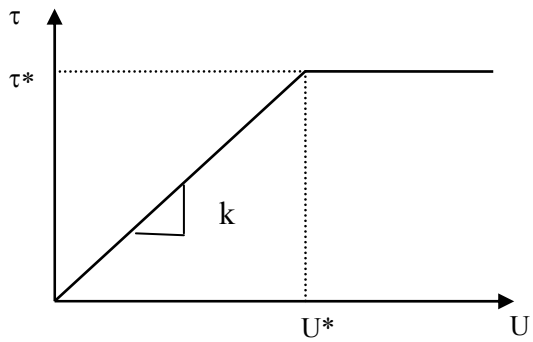

Figure 9. Local friction model

The mobilization of the reinforcement is divided into three stages:

1st stage U_T < U*: the reinforcement is in the mobilization state.	
For U < U *, all the moving strap part follows a law :	τ (x)= k.U(x) [1]
The pull-out tensile-strain dT applied for any dx length element along the strip is given by:	$dT(x) = p\tau x dx$ [2]
The ε(x) local deformation at the x point is deduced from the modified tensile-strain law (figure 8).	$\frac{dU(x)}{dx} = \frac{T(x)}{J} + \varepsilon 0 = \varepsilon(x)$ [3]
Combination of expressions [1] [2] and [3] allows the writing of the local displacement U(x) in the differential equation form [4].	$\frac{dU^2(x)}{dx^2} - \beta^2 U(x) = 0$ [4]
The origin of the x-coordinates is supposed to be located in Q, free extremity of the strap. Boundary conditions are as follows: T(x = 0) = 0, T(x = L) = T_T, U(x = L) = UT.	with $\beta^2 = \frac{pk}{J}$ [5]

The resolution of the differential equation [4] leads then to the tow following values: Equation [6] led to U(x) = 0 at the point M (equation [8] and [8bis]): In the same way, the equation [7] leads to T(x) = 0 at point N such as: At N, Tx = 0, we have (dU/dx) = T/J + ε_0, thus, the slope curve U(x) is such as (dU/dx) = ε_0.	U(x) = (UT).[ch(β.x)/ch(β.L)] - (ε0/β).[sh(β.(L-x))/ch(β.L)] [6] T(x)=(β.J.UT).[sh(β.x)]/[ch(β.L)] - (J.ε0).[1 - ch(β.(L-x)) / ch(β.L)] [7] th(β.x) = th(β.L) - (β.UT/ε0) / ch(β.L) [8] x = ath(th(β.L) - (β.UT/ε0) / ch(β.L))/β□ [8bis] th(β.x/2) = th(β.L) - (β.UT/ε0) / ch(β.L) [9] x = 2 ath(th(β.L) - (β.UT/ε0) / ch(β.L))/β□□□□[9bis]
The equations [6] and [7] show that for x = 0, U(x) is negative, which is physically impossible. This result is related to the fact that all the reinforcement length (L) was considered in the calculation whereas the anchoring laws suppose that there is a dead zone at the rear of the inclusion. Therefore, to superimpose points M and N and to represent a strap progressive mobilization, equations [8] and [9] are expressed about a variable origin 0 at x-coordinate x_0 such as that at any moment during the test, the mobilized friction length corresponds to l_1 = L – x0. The length of the strap l_1, mobilized at any moment during the test, will be given by the expression [10].	
When the head displacement reaches the limit value U * (UT=U *), the strap length L* obeying a type (1) law is given then by expression [11]. The combination of the previous expressions makes it possible to calculate the total tensile-strain value TT at the head versus imposed displacement UT . The transformation of the equation 12 gives the non-dimensional expression 12ter. This last equation allows us to determine the parameters τ_0 and k by plotting graph TT/J – UT²/TT	sh(β.L_1) = (β/ε_0).U_T [10] sh(β.L*) = (β/ε_0).U* [11] T_T = β.J.U_T.th(β.L_1/2) = Jε_0 (ch(β.L_1) – 1) [12] T_T/J = Pk (U_T^2/T_T) - 2ε_0 **[12ter]**
2nd stage Ui > U*, Uq<U*: friction is saturated at the head and in mobilization at the rear.	
Friction is saturated at the head over a length L2. At the rear, over a length Lp, the friction follows a type (1) law; the end Q is still not released. In the zone 2, the friction parameter becomes τ □x = τ *. Compared to the variable origin O, the solution in the zone (2) becomes: Applying the initial conditions x = L at the reinforcement head T2 = TT and U2 = UT : For U1 = U2 = U*, we have T1 = T2 ([13] = [7]), it leads to two expressions [15] and [16] Equation [16bis] allows, as in the first stage, to determine the parameters τ_0 and k by plotting the graph (TT/J) – (UT²- (UT – U*) 2 /TT). The equations [11] and [16] allow to calculate the length L2 obeying the type (2) law versus the head displacement UT : For L2 = (L – L*), the equation [17] gives the	$$\frac{dU^2(x)}{dx^2} - \frac{p\tau^*}{J} = 0$$ $T_2(x) = T_T - \tau.(L_2 + L^* - x)$ [13] $U_2(x) = U_T - (\varepsilon_0 + T_T/J).(L_2 + L^* - x) + (\tau^*/J).(L_2 + L^* - x)^2$ [14] T_T = β.J.U*.th(β.L_p/2) + p.τ*.L_2 [15] U_T = U* + β.L_2.U*.th(β.L*/2) + (τ*/J).$(L_2)^2$ + ε_0.L_2 [16] T_T/J = p k (U_T^2-(U_T – U*) ^{2}/T_T) - 2ε_0 [16bis] $[\beta.L_2.th(\beta.L^*) + 1]^2 = 1 + 2.[th(\beta.L^*)]^2.(U_T/U^* - 1)$ [17]

necessary displacement UT = UL to release the strap.	
3rd stage Uq > U*: the strap is entirely released. The previous expressions remain valid with the proviso of replacing the length L* by a L1 value decreasing gradually by the value L* to a zero value.	
After transformation, both values TT, UT become:	$T_T = [J.\varepsilon_0].[[sh(\beta.L^*)].[th(\beta.L_1) + \beta.(L-L_1)] + [l/ch(\beta.L_1) - 1]]$ [18] $U_T = U^* + [\varepsilon_0.(L-L_1)].[[sh(\beta.L_p)].[th(\beta.L_1) + \beta.(L-L_1)/2)] + [l/ch(\beta.L_1)]]$ [19]
Umax displacement making it possible to reach the Tmax tensile-strain value is obtained for L1 = 0.	$U_{max} = U^* + \varepsilon_0.L + \tau^*.(L)^2/j$ [20] $T_{max} = p.\tau_p.L$ [21]
Equation [21bis] allows, as in the first and second stage, to determine the parameters ε_0 and k.	$T_A/J = p\ k\ ([U^2_T - (U_T - U_T)^2 - U_Q{}^2]/T_T) - 2\varepsilon_0$ [21bis]

The expressions [6] to [21] allow graphical translation of some characteristic relations of the anchoring inclusions behaviour, and in particular those which could be compared with the experimental curves, curve (TT, UT) at the head and curves U(x) along inclusions.

ANALYTICAL MODELING OF THE PULL-OUT TESTS

To model correctly the strip behaviour by analytical calculation, the reinforcement characteristics and friction model parameters are deduced from experimental tests (Table 2). In fact, the reinforcement elongation modulus (J), maximum soil/reinforcement friction (τ*) and relative soil/reinforcement displacement corresponding to total mobilization of friction (U*) are deduced by fixing the theoretical curve of the displacements at the head of the strap on the experimental curve (Figure 10). In addition, k and ε_0, are determined theoretically from the equation [12ter] by plotting the graph T_T/J vs U_T^2/T_T (Figure 11) or by expressions [16bis] and [21bis].

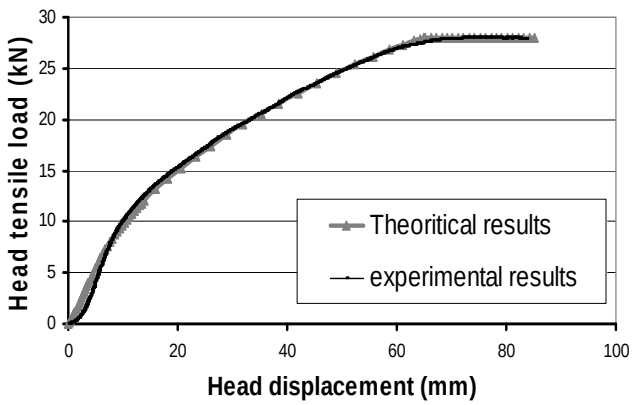

Figure 10. Tensile/displacement theoretical curve fixed on the experimental results.

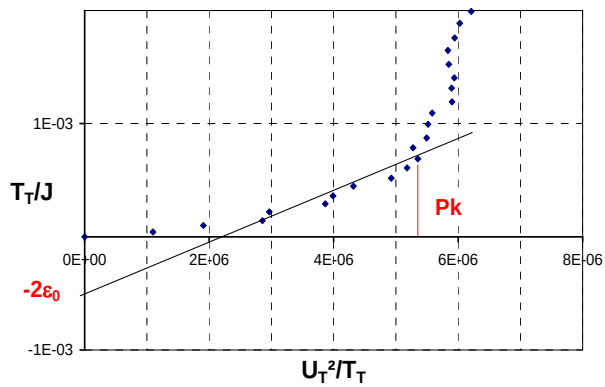

Figure 11. Determination of ε_0 and k

The tensile-load model taken into account in the analytical method does not correspond exactly to that of a synthetic reinforcement. Indeed, the curve obtained from tensile tests on free synthetic strips gives a non-linear curve and a variable elongation modulus (between 340 and 1000 kN) whereas the modulus used in the analytical calculation is constant because the tensile-strain relationship is supposed to correspond to a straight line (Figure 12). However, for the test carried out under a confinement stress of 100 kPa, the maximum strip deformation is equal to 3%. Thus, the real elongation modulus varies between 1000 and 380 kN. To simulate the pull-out test well under confining stress equivalent to 100 kPa, the best elongation modulus considered in the calculation is equal to 450 kN.

Table 1. Elongation modulus confrontation

ε (%)	0.5	1	2	3	4
Real J (kN)	700	500	340	380	500
Theoretical J (kN)	450				

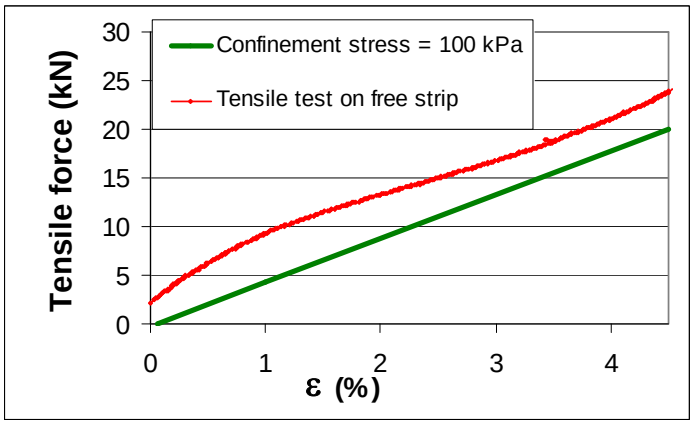

Figure 12. Confrontation of analytical and real tensile-strain model of the strip

After determination of all the parameters mentioned above (Table 2), one can calculate displacements along the reinforcement by the analytical equations (Figure 13). Comparing the theoretical and experimental results shows that the analytical method makes it possible to reproduce the delayed displacement of the reinforcement well.

Table 2. Analytical parameters calculation

Model	Vertical stress (kPa)	Strip length (m)	Strip width (m)	J (kN)	U* (m)	ε_0	F*
Modified Tensile-strain	100	1,9	(0,05) x 2	450	0.005	0.0006	0.85
Classical	100	1,9	(0,05) x 2	450	0.005	-	0.85

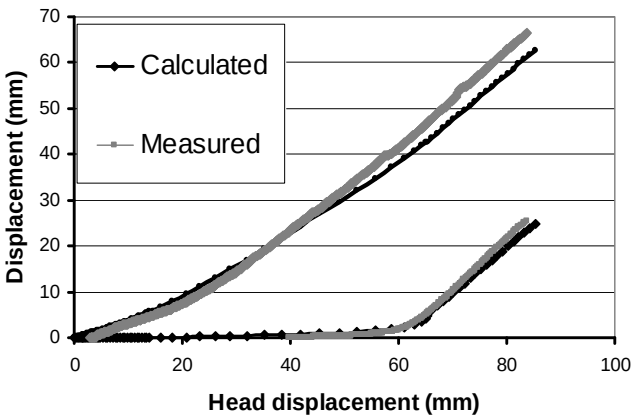

Figure 13. Displacement at the rear and the center of strip versus the head displacement, (vertical stress: 100 kPa).

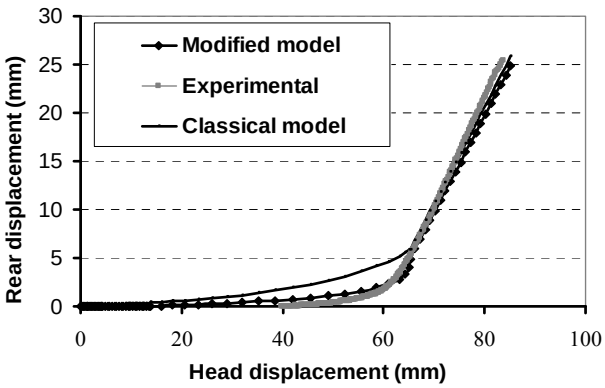

Figure 14. Confrontation between the two analytical methods and experimental results (vertical stress: 100 kPa).

To compare the results obtained from the method of modified tensile-strain model to those obtained from a classical method, represented in Figure 14, rear displacements versus head displacements of synthetic strip determined from experimental results and those from two different analytical methods. The classical method (Classical model) is based on classical friction and tension models. It considers the tensile-strain relationship as satisfying Hooke's law T = J□ε (J constant) □and the ground-inclusion interface friction relation is assumed to be of Cambefort's type (Schlosser 1981, Segrestin and al. 1996). Figure 14 shows that the classical model considers a mobilization of the entire strip at the beginning of tension. This assumption leads to an important shift between the experimental curve and the results obtained from the classical analytical model. In fact, the experimental results show that the rear point of the strip moves only when the head point is fully mobilised. This delayed mobilization is modelled well in the second method (modified model) by considering an initial deformation threshold ε_0. Indeed, the error calculation (err), between the theoretical and experimental curves ($err = \sqrt{\sum (yi_{calculated} - yi_{measured})^2}$, where yi represent the rear displacement

evolution on the curve, Figure 14) gives an err = 16.05 between the experimental curve and the modified model curve whereas for the classical model the error is equal to 33.028 compared to the experimental curve.

CONCLUSION

The modelling of the behaviour of a synthetic strip anchored in the ground and subjected to a tensile load at the head, by an analytical method, requires an analytical model that takes into account the progressive mobilization of the strip. However, this progressive mobilization phenomenon is governed by several parameters. First of all, the stiffness of the reinforcement; a confined flexible strip moves gradually part by part from the head to the rear due to its elongation. Consequently, friction is also mobilized gradually from the head to the rear. This strip behaviour is modelled analytically by considering three successive stages of friction saturation. At the beginning of the application of tensile load, the reinforcement is supposed to be mobilized in shear at the head. Then, in the second stage, the friction is supposed to be fully mobilised at the head and in a partial mobilization state at the rear. Finally, at the last stage the strap is considered to be entirely released. The second parameter that governs the strip progressive mobilization is related to the confinement stress. When this one is significant, the strip deformation is more pronounced, thus the delay in mobilization will be more significant. As showed previously, the increased level of confinement stress increases the deformation of the strip; however, the elongation modulus varies according to the strip deformation state. Hence, to reproduce this phenomenon in the analytical model, it is necessary to vary the elongation modulus as the confinement stress varies. The last parameter relates to the set up of the reinforcement. The initial deformation at the head of the synthetic reinforcement at the beginning of the tensile load application is often related to the manner of its set up. Due to its flexibility, the reinforcement often has an irregular surface which increases the delay in mobilization. Including an initial deformation ε_0 into the tensile-strain model allows this phenomenon to be taken into account.

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