Earth Reinforcement Practice, Ochiai, Hayashi & Otani (eds) © 1992 Balkema, Rotterdam. ISBN 90 5410 093 1

Pull-out behaviour of reinforcements – Centrifuge tests and theoretical validations

J.P.Gourc & P.Villard
IRIGM, Grenoble University, France

Y.Matichard
LRPC, Nancy, France

ABSTRACT : Use of the "displacements method" is becoming increasingly widespread in the dimensional design of geotextile-reinforced earth embankments. This method allows evaluation of deformability of the structure based on the pull-out behaviour of geotextile sheets. The pull-out calculation uses an analytical theoretical model. The main objective of this paper is to validate this analytical calculation on one hand by centrifuge tests, and on the other hand by finite element computations.

1. INTRODUCTION

In the field of soil reinforcement, it is common practice to classify the reinforcing inclusions according to their extensibility.

Extensibility is characterised by tensile strength tests on the armouring material. The tensile stiffness J expresses the relation between the pull-out force α (kN/m) and the corresponding deformation ε of the inclusion.

For a buried inclusion of length L_A, subjected to a pull-out test, the displacement u_A of the top of the structure, point A, is a function of two variables: the tensile stiffness J of the inclusion, and the friction behaviour of the soil/inclusion interface. This behaviour may be determined by a laboratory friction test and represented schematically as on figure 1: τ_P, u_P are the friction variables under a normal stress σ_z.

For an inclusion of tensile stiffness J, independent of the deformation ε, and taking into account the above friction (τ_P, u_P), the pull-out force α_A may be determined theoretically as a function of the displacement u_A (Gourc, 89).

To characterise the deformation of a reinforced earth structure in stable state, the authors proposed the "displacements method" (Gourc, 86), with its associated software (Delmas, 86).

Displacement Δ at the top of the reinforced earth embankment is calculated assuming that each reinforcement sheet is sujected to pull-out forces in an active zone, length LAa , pull-out force aA (UAa), and in a passive zone, length LAp , pull-out force aA (UAp) (figure 2). The theoretical pull-out calculation is effected as shown above.

Correct estimation of the pull-out behaviour

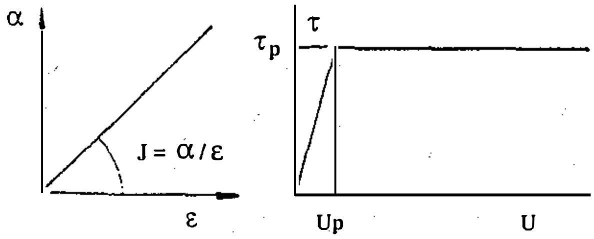

Fig.1 : "Displacements Method" : Proposed relationships for tensile and friction behaviour of the inclusion

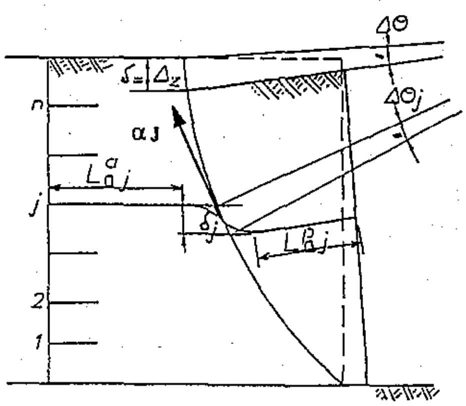

Fig.2 : "Displacements Method" : Proposed mechanism

is thus shown to be particularly important to validate the displacements method. It was therefore decided to check the validity by two methods, one experimental and the other theoretical.

Experimental method: chapter 2 describes pulling tests in a centrifuge on an extensible geotextile armour, and on an inextensible rough iron armouring, under the same conditions.

Theoretical method: the analytical calculation presented above ignores the deformation of the earth embankment surrounding the inclusion. A finite-element calculation (chapter 5) enabled this adjacent soil deformation to be taken into account.

2. PULL-OUT TESTS IN A CENTRIFUGE

These tests were performed in the centrifuge of the Ponts et Chaussées laboratory in Nantes (Blivet, 86). This installation has an effective diameter of 5.5 m, and can subject a mass of 2 tonnes to an acceleration of 100 g.

The test procedure, presented on figure 3, consists in entraining a 20 cm inclusion in the direction of pull over a width of 50 cm. The test chamber is 20 cm high, 46 cm long and 80 cm across.

To avoid any influence of the front wall of the chamber (at A), the inclusion is provided with a front sheet. The variables measured during the pull-out test at constant speed (2 mm/min) are the pull-out force α_A (kN/m), the top displacement u_A and the displacements $u_{1,2,3,4,5}$ of sheet points spaced at 5 cm intervals, called $G_{1,2,3,4,5}$, for the geotextile, and $I_{1,2,3,4,5}$ for the rough iron reinforcement.

Since the extension of the front sheet is negligible, we obtain $u_1 \approx u_A$, the slight difference corresponding to the fact that measurement point 1 is not on the axis of symmetry of the inclusion.

Also measured are the horizontal displacements of points in the soil, defined on the x-axis at levels 1,2,3,4,5 and in elevation at z = -1cm, +1cm and +5cm, as well as the vertical displacements of three points (a), (b) and (c) of the free surface.

The soil is a dry Fontainebleau sand (D_{50} = 0.18 mm , C_u = 1.6 , γ_d= 15.5 kN/m^3 , C= 5 kPa and φ = 37°).

The inclusions are a Bidim b7 needle-punched unwoven geotextile and a metal sheet lined with abrasive paper. The front sheet is of the same type as the metal sheet but smooth.

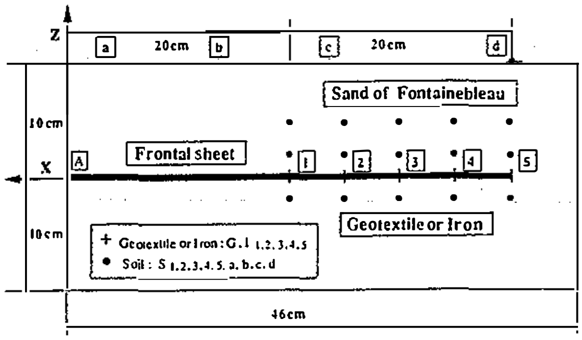

Fig 3. : Pull-out test, centrifuge experimentation

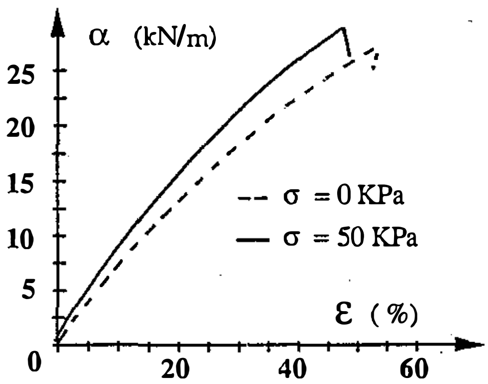

Fig.4 : Experimental tensile behaviour of the geotextile : influence of the confining pressure

The behaviour of the unwoven geotextile under tensile stress is influenced by the perpendicular stress σ_z applied to the reinforcement sheet, as shown by (McGown, 82). The result of a pull-out test on this geotextile (sample 10 cm by 20 cm) is illustrated, with σ_z = 0 and σ_z = 50 kPa (Blivet, 92). Thus, for the analytical pull-out calculation presented in chapter 1, the tensile stiffness (deduced from figure 4) will be assumed to be J = 106 kN/m for σ_z = 46.5 kPa, the normal tensile stress in the centrifuge.

The friction behaviour of the soil/inclusion interface is evaluated by means of a modified shear box (10 cm by 10 cm). The results obtained with the geotextile are presented on figure 5. They correspond to a threshold friction angle of φ_G = 31.5°. For σ_z = 46.5 kPa, it is considered that τ_p = 28.5 kPa and u_p = 2.4 mm.

The same type of friction test performed on the metal front sheet gave φ = 20°.

By sticking an abrasive lining on this type of rough iron sheet, the measured friction angle of the metal inclusion is found to be the same as for the geotextile, $\varphi_I = \varphi_G$, but the extreme value

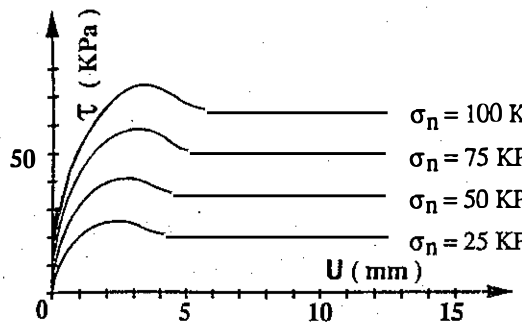

Fig. 5 : Experimental friction behaviour for geotextile in contact with sand

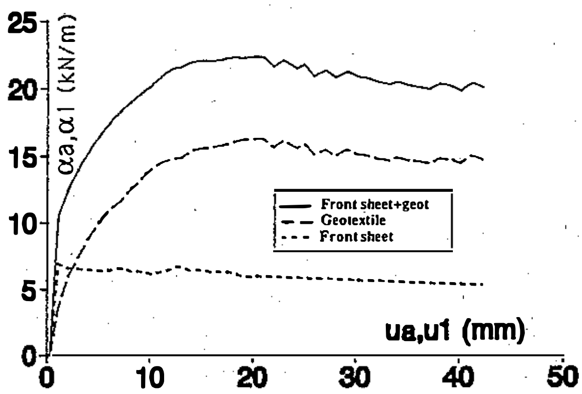

Fig. 6 : Centrifugal pull-out test

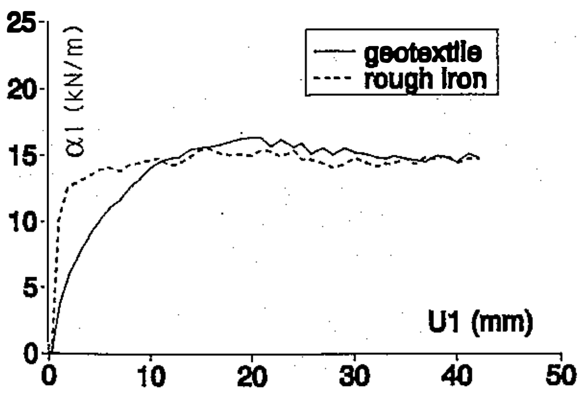

Fig.7 : Influence of the extensibility of the inclusion on pull-out behaviour

of shear stress τ_P is obtained for a displacement $u_P = 2.5$ mm.

3. CONDITIONS OF SIMILITUDE

The centrifuge experiments were conducted under an acceleration equal to 30 g.

The sample tested in the centrifuge is assumed to be modelled at a scale of $l^* = 1/30$, with $l_{Model} = l^* \times l_{Real}$. It is to be confirmed that under these conditions the stress condition is identical for the model and the real case ($\sigma^* = 1$). For the same Fontainebleau sand on the model and in the real case, the same state of deformation is obtained ($\varepsilon^* = 1$).

To obtain identical deformation of the geotextile inclusion ($\varepsilon^*_G = 1$), bearing in mind that the ratio of pull-out forces on the model and in reality corresponds to the linear scale ($\alpha^* = \sigma^*.l^* = l^*$), the geotextile is to be selected with a tensile stiffness scaled down linearly ($J^* = \alpha^*/\varepsilon^*_G = L^*$). Thus the geotextile inclusion on the model simulates a "real" geotextile of stiffness $J_{Real} = 30\, J_{Model}$, of length 6 m, buried at a depth of 3 m. This led to selection of a geotextile of limited tensile stiffness for the model (unwoven, with a weight per unit area of 340 g/m²).

The only condition that cannot be checked for similitude concerns the law of friction at the interface: for geotextiles, modelled and in reality, with the same surface state and the same Fontainebleau sand, the friction law will be the same: $(\tau_P)_M = (\tau_P)_R$ and $(u_P)_M = (u_P)_R$, which contradicts with $(u_P)_M = l^*.(u_P)_R$, a condition which cannot therefore be verified. Since the values of u_P are overestimated on the model, the pull-out displacement u_A is likewise overestimated.

4. EXPERIMENTAL RESULTS IN CENTRIFUGE

A pull-out test is carried out under the same conditions for the extensible sheet (geotextile) and for the "inextensible" metal sheet (rough iron), both inclusions being provided with the same front sheet. A complementary test is performed on the front sheet alone. By subtraction, the pull-out stress on the inclusion, without the front sheet, is thus obtained (figure 6).

Figure 7 enables comparison of the pull-out stresses as a function of stiffness of the inclusion, since the interface characteristics are very close (figure 7). The same maximum pull-out stress is in fact observed (corresponding to the same value of τ_P), but is obtained under a smaller displacement with the metal inclusion.

Figure 8 presents the displacements of points $G_{1,2,3,4,5}$ of the geotextile inclusion as a function of displacement at the top of the sample: $u_A = u_1$. Progressive sliding of the inclusion is observed, initially only at the top.

Figure 9, more original, shows the variation of soil displacement measurements during the pulling of the inclusion, at $z = +1$ cm, in the

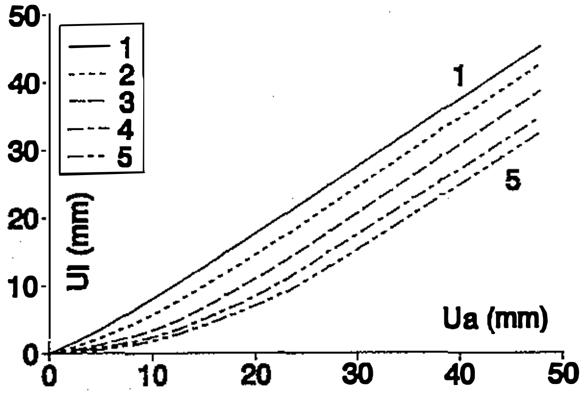

Fig. 8 : Displacements of the geotextile inclusion during the pull-out test

upper part, and z = -1 cm, in the lower part.

It can be seen that displacements are non-symmetrical relative to the inclusion plane, displacements below the inclusion being much lower (in a ratio of 1 to 10).

Displacements of the earth embankment are greater with the metal inclusion, which is not subjected to progressive sliding like the geotextile.

Figures 10 and 11 represent the comparative displacements of the two inclusions and of the adjacent soil for the same top displacement u_A = 50 mm. In both cases, it can be observed that at the bottom of the inclusion, the soil is in the active state (positive horizontal deformation of the soil), whereas at the origin of pull-out, the soil is in the passive state (negative horizontal deformation of the soil, this phenomenon being more pronounced with the metal inclusion).

5. THEORETICAL MODELLING

Considering the particular features of the pull-out test (substantial relative displacements between the geotextile and the soil), a computational code specific to interface problems involving high displacements had to be created. The method proposed for modelling the interface is an adaptation of the finite-element method for major deformations (second-order relations between displacement and deformation), which consists in applying an iterative method, in which local conditions of interaction between the nodes of the interface are imposed on each incremental calculation.

The areas on either side of the interface are discretised individually. The interface is thus materialised by two lines of nodes (figure 12). This discretisation results in the matrix system (F) = (K) (U), which represents the individual equilibrium of each node of the mesh.

The resulting conditions of local interaction between the nodes B, I and J, which after displacement and deformation are on either side of the interface, are as follows:

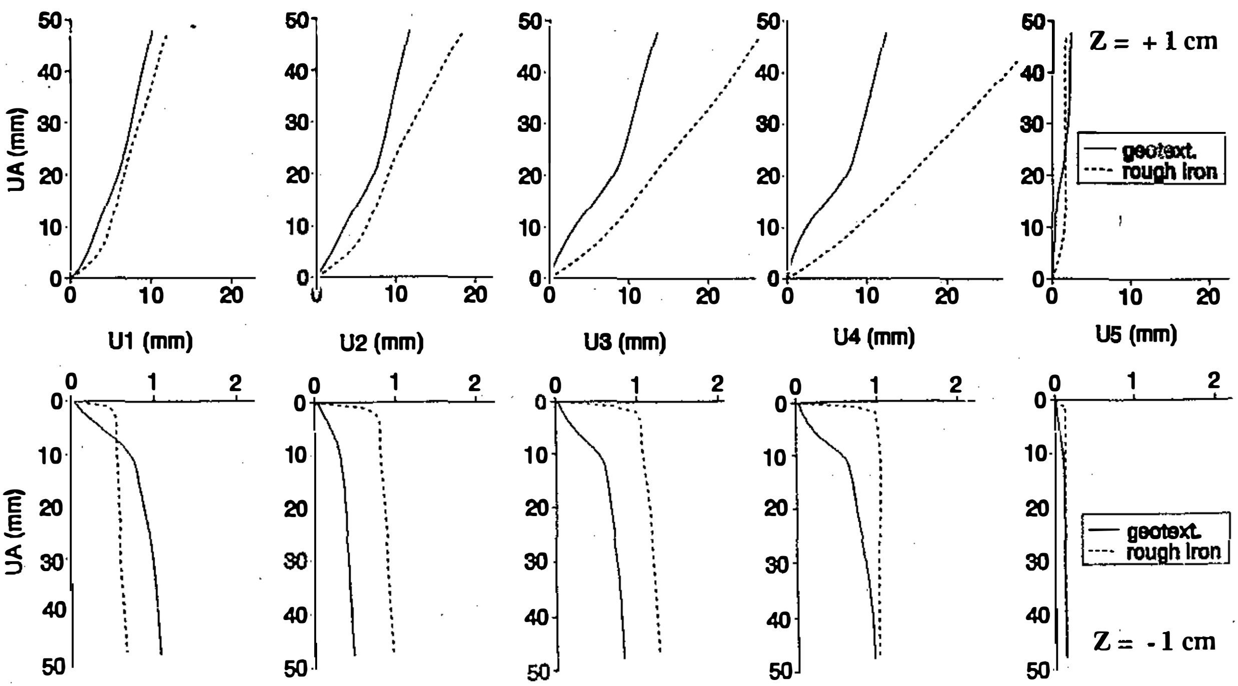

Fig. 9 : Soil displacements in the vicinity of the geotextile

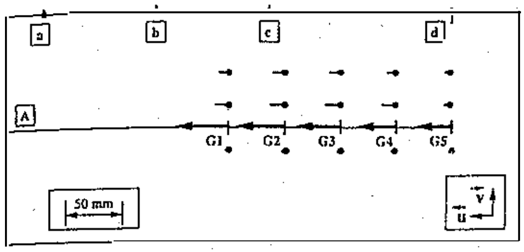

Fig.10 : Soil and geotextile displacements for $U_A = 50$ mm

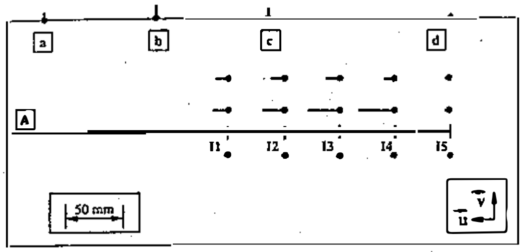

Fig.11 : Soil and rough iron displacements for $U_A = 50$ mm

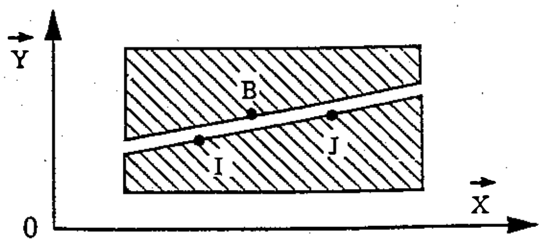

Fig 12 : Modelling the interface

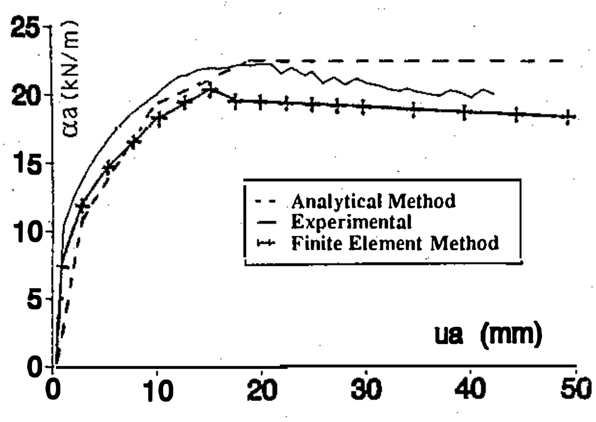

Fig.13 : Front sheet + geotextile : theoretical and experimental pull-out behaviour

- a condition on displacement of the nodes B, I and J (condition of non-interpenetration of zones),
- a condition of overall equilibrium of the point of contact (condition of equlibrium of forces on either side of the interface), which substitutes for the equations of individual equlibrium of the nodes B, I and J.

The first condition results in elimination of one of the displacement variables at each of the nodes B of the contact zone. The second results in elimination of one equation of the matrix system (F) = (K) (U). The resulting matrix system (F') = (K') (U') is a system of n-x equations and n-x unknowns (x being the total number of nodes B of the contact zones), which have simply to be resolved. The relations between displacement and forces are obtained by an approximation calculation as a function of the values obtained at the previous iteration, which implies application of an iterative method tending progressively towards the solution.

This method, which is written into the computational code GOLIATH designed by the IRIGM, presents the following advantages:

- individual discretisation of the zones on either side of the interface (each node of the underlying zone does not necessarily correspond to a node of the overlying zone),
- there is no numerical problem related to distortion of elements at the interface,
- possibility of obtaining a variable law of behaviour in the contact zone (displacement of a node from one zone to another zone of different characteristics),
- no restriction on the value of relative displacement between zones.

Application of this method to the case of a geotextile inclusion with its protective sheet is presented by way of example.

The theoretical curves for the inclusion (pull-out stress, friction) are obtained by smoothing the experimental curves (figures 4 and 5). The soil is assumed to be elastic (E = 30 000 kPa, ν = 0.33).

The theoretical diagrams obtained (pull-out force: figure 13 - displacement of points on the geotextile: figure 14) are in effective agreement with the experimental results.

It is interesting to observe that the analytical calculation presented in chapter 1 (displacements method), although not taking into account the deformation of soil around the inclusion, and based on simplified variables (J, τ_P, u_P) gives a good approximation of the pull-out relationship $\alpha_A(u_A)$. This substantiates the calculation proposed in the "displacements method".

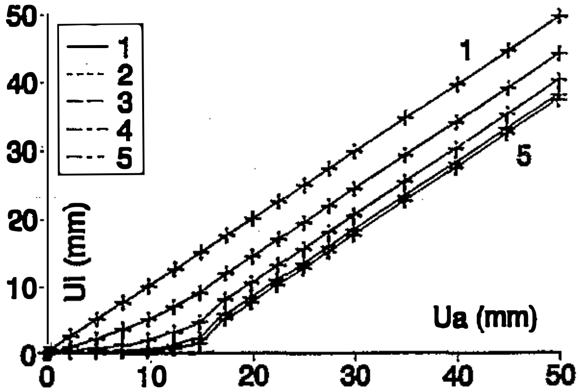

Fig.14 : Theoretical displacements of the geotextile inclusion during the pull-out test

6. CONCLUSIONS

• These centrifuge pull-out experiments have enabled confirmation of the influence of extensibility of the inclusion. This influence is effective on the displacement of the top of the structure necessary to mobilise the maximum pull-out force.

• The deformations of the earth embankment adjacent to the inclusion are a function of extensiblity of the inclusion.

• The finite-element calculation succeeded in reproducing precisely the experimental pull-out test results obtained on the geotextiles in the centrifuge.

• The analytical calculation of the pull-out force as a function of top displacement proposed in the "Displacements Method" appears as a satisfactory approximation of the finite-element calculation, much more cumbersome to apply, and may therefore safely be adopted for design purposes.

REFERENCES

Blivet, J.C., Matichard, Y., Delmas, Ph., Garnier, J. (1986). Model test in a centrifuge of a wall reinforced with geotextile. Third International Conference on Geotextiles. Vienna Austria.

Blivet, J.C., Matichard, Y., Levacher, D., Mfouti (1992). Mechanical behaviour of geotextile in the design of permanent reinforced structures. International Symposium on Earth Reinforcement, Kyushu 92, Fukuoka Japan.

Delmas, Ph., Berche, J.C., Gourc, J.P. (1986). Dimensional design of geotextile-reinforced structures; CARTAGE program. Ponts et Chaussées Bulletin n° 142.

Gourc, J.P., Gotteland, Ph., Delmas, Ph. (1989). Parametric study of geosynthetic reinforced retaining walls using the "displacements method". Geosynthetics '89. San Diego. USA.

Gourc, J.P., Ratel, A., Delmas, Ph. (1986). Design of fabric retaining walls: the "Displacements Method". Third International Conference on Geotextiles. Vienna Austria.

McGown, A., Andrawes, K.Z. (1982). Load-extension testing of geotextiles confined in soil. Second International Conference on Geotextiles. Las Vegas USA.