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Cellular walls associated with geosynthetics: A laboratory model study

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ABSTRACT : The development of structures using soil reinforced by geosynthetics involves using specific facings that are economic, deformable and aesthetic. Cellular walls, associated with geosynthetics, are thus widely used for the construction of motorway embankments in France. A two-dimensional scale model study was carried out in order to test critical conditions for this type of structure (mode of failure, and calculation of the facing/reinforced soil embankment system).

1. INTRODUCTION

The application of a variety of facing techniques in association with retaining embankments of geotextile-reinforced soils has led to a new stage in development of this type of structure.

The present case study concerns the use of facings made with superimposed concrete cells (called Löffel stones), between which the geotextile sheets are held. The French motorway construction company Scetauroute frequently adopts this procedure as a means of increasing the slope of road embankments. The design of these structures is at present based on the calculation methods conventionally used for geotextile-reinforced soils (Gourc, 87).

It was considered of value to undertake a comparative study of cellular facing structures and retaining structures where the facing is formed simply by overlapping of the horizontal geotextile reinforcing sheets. A study on real-life structures is in progress, a result of collaboration between Scetauroute and Irigm (Grenoble University), but only scale model testing allows a full study of all variables.

Some of the results obtained after a large number of tests are presented in this paper. The preliminary phase of this research, with different materials, was presented in an earlier paper (Gourc, 90).

2. MODELLING

2.1 The soil

The soil is a Schneebelli material, made up of rolled duralumin (diameters 3 and 5 mm). This powdery soil has a density of $\gamma_s = 22.5\ kN/m^3$, and angle of friction $\phi = 25°$. The deformation tested here is therefore on a single plane.

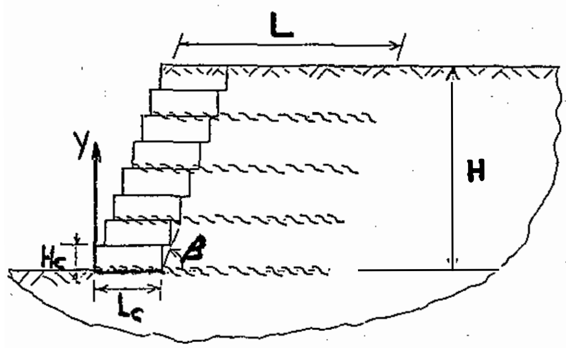


figure 1 : Geometrical parameters for the model with cellular facing

2.2 The cellular wall

The real facing is assumed to be formed by hollow concrete cells. The equivalent density of the cells filled with soil is $\gamma_c = 19.2\ kN/m^3$. The individual cell width is $L_c = 0.09$ m and height $H_c = 0.035$ m.

The cells are provided with notches so that they effectively interlock, with a constant embankment slope β (figure 1).

The cells can pivot around each other, and provision is made for them to hold the reinforcement sheets, but sliding of one cell on another is precluded.

2.3 The reinforcement sheets

Two types of reinforcement are considered: thermo-bonded non-woven geotextile sheets (weight per unit area $\mu = 68\ g/m^2$, failure stress α_f

= 5 kN/m) and an absorbent cellulose paper (μ = 17 g/m^2, failure stress α_f = 0.14 kN/m).

This gives two different modes of failure for reinforced soil retaining walls: failure by sliding of the geotextile inclusions, and failure by rupture of the cellulose inclusions.

The pull-out resistance of these inclusions was tested previously (Gourc, 90). The resulting angles of friction were ϕ_g = 20.5° for the rolled duralumin/geotextile contact, and ϕ_p = 18.5° for the rolled duralumin/paper contact surface.

The reinforcement sheets have a fixed horizontal length L (total length up to the facing, including the length held between two cells).

2.4 Standard test

The rolled duralumin retaining embankment was placed layer by layer at the same time as the cellular facing. Reference markers placed on the material allowed evaluation of displacement, based on photographs taken at each stage of construction. The sheets were placed horizontally at an interval ΔH equal to the height of one cell (0.035 m), two cells (0.070 m) or more.

Construction continued up to the limit height (H_{max}) at which the reinforced soil structure became unstable.

The displacement of one point on the structure (marker placed on a soil layer) between two stages of construction was obtained by processing photographs on a digital graphics plotter. This determined the limits of the active zone, referred to here as the slip line.

2.5 Parametric study

Four different types of structure were considered:

- geotextile or paper facing,
- cellular facing with non-reinforced soil,
- cellular facing with soil reinforced by sheets not linked to the facing cells,
- cellular facing with soil reinforced by sheets linked to the facing cells.

Three facing angles were reproduced, β = 60°, 80° and 90°, and two reinforcement sheet lengths, L = 0.24 and 0.33 m.

It is important to underline that the model was designed (and calculated) like a real-life structure, i.e. at 1:1. This is because it is not feasible to respect all the conditions of similitude with a scale model of such a structure.

Nevertheless, the information derived from this parametric study is of fundamental importance concerning the mechanisms of failure.

3. LIMIT STATE CALCULATION

The photographic study allows delimitation of the unstable zone by a slip line. This slip line is then approached by three lines, one "bilinear" (two segments), another "circular", and the third "combined" (arc of circle plus a segment).

The retaining embankment in the limit state is studied on the basis of two alternative methods used in slope stability calculation (Gourc, 87):

- the "perturbation method", developed in France, based on isostatic slices, which may be applied to a slip line of any form. This is annotated (P2C) where the calculation involves two unknown variables and (P1C) where there is only one unknown variable ("bilinear" line).
- the "double block method", annotated (2B), which considers the equilibrium of the sliding zone divided into two blocks with a vertical interface. The associated sliding line is bilinear.

These general methods, applied to the case of reinforced soils, must take into account the stability gain due to the tensile strength of the reinforcement sheets.

- If the reinforcement sheets are totally included within the unstable active zone, limited by the slip line, no tensile force is taken into account in the calculation.
- If the reinforcement inclusions intersect the slip line, the tensile force of the reinforcement mobilised in the passive zone is introduced as

$$\alpha_i = \min(\alpha_{Ai}, \alpha_{fi})$$

with : α_A, the maximum force corresponding to sliding of the reinforcement and α_f, the maximum force corresponding to rupture of the reinforcement.

Calculation of the equilibrium limit, taking into account possible tensile forces, enables determination of the coefficient of safety F_{SC} against shear along the slip line.

Depending on the chosen method of stability calculation and the slip line, different values of safety coefficient are obtained (figure 3). The value of F_{SC} is all the more satisfactory as it tends towards 1. This approach allows systematic testing of validity of the different methods for analysis of equilibrium limits.

A complementary calculation was proposed: instability of the reinforced soil retaining structure with cellular facing corresponds to the equilibrium limit of the cellular facing and of the reinforced soil embankment without facing .

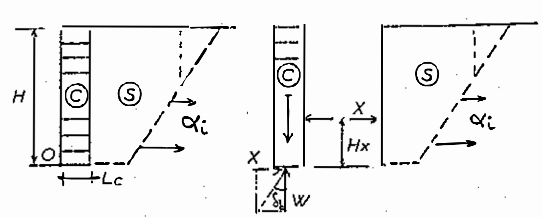


figure 2 : Proposed mechanism for the interaction cellular wall-reinforced soil

The equilibrium limit of these two components of the structure was thus studied separately (Gourc, 90, figure 2). The interaction between the reinforced soil and cellular wall is represented schematically by a horizontal force X (unless $\pi/2 - \beta > \phi$), situated at height H_x. This force is the resultant of the soil thrust P on the facing and the tensile strength T_i at the connection between the reinforcement sheets and the cells:

$$X = P - \Sigma T_i$$

The assumption of equilibrium limit of the cellular wall leads to evaluation of X, once H_X has been fixed (for this first step, a straightforward assumption was made: $H_X = H/3$), by introducing a pseudo-coefficient of thrust K_X:

$$X = 1/2 \,.\, K_X \,.\, \gamma \,.\, (H_{max}/\sin \beta)^2$$

With the value obtained for X, the stability of the reinforced soil embankment without facing is then calculated.

F_{SX} is taken as the coefficient of safety against shear along the same slip line as F_{SC}. The calculation method is considered satisfactory if, for a F_{SC} value close to 1, a F_{SX} value close to 1 is obtained.

4. EXPERIMENTAL RESULTS

4.1 Influence of density of reinforcement sheets

For the study of the first variable, the method is set out in detail. Since the same method is applied for the other variables, it is not described fully in the subsequent paragraphs.

Table 1 : Results for the cellular facing model ($\beta = 60°$). Influence of the density of reinforcement sheets. F_{SC} for combined slip lines.

N°	α_f kN/m	L (cm)	ΔH (cm)	Hmax (cm)	F_{SC}	K_X	F_{SX}
1P	0,14	33	7 (0)	49	1,00	0,106	1,02
2P	0,14	33	7	49	1,00	0,106	1,15
3P	0,14	33	3,5	63	0,99	0,082	1,10
2G	5	33	7	70	0,94	0,074	0,93
3G	5	33	3,5	71	0,95	0,073	0,84

Table 2 : Tensile forces in the sheets taken into account for the calculation (cases of the table 1 - $\beta = 60°$)

	$\alpha = \min(\alpha_A, \alpha_f)$ (kN/m)				
y \ N°	1P	2P	3P	2G	3G
0,14	0	0,14	0,14	0	0
0,105	X	X	0,14	X	0
0,07	0,14	0,14	0,14	0	0
0,035	X	X	0,14	X	0
0	0,14	0,14	0,14	0,463	0,33

4.1.1 *General methodology*

The first case tested concerns cellular walls associated with paper reinforcement sheets, on a slope $\beta = 60°$. Failure is obtained systematically by rupture of the paper sheets at the intersection with the slip line (cases 1P, 2P, 3P on figure 4).

The three types of slip line are considered, all passing through the points of rupture of the reinforcements and limiting the unstable zone.

In each case, the safety coefficients F_{SC} and F_{SX} are calculated (figure 3), after calculation of the tensile force mobilised (considering only those reinforcement sheets that intersect the slip line).

Generally speaking, the combined slip line, with its forward edge on or below the plane of the reinforcement sheet, is the most satisfactory. In the present example, the circular slip line gives a good approximation. In both cases, the safety coefficient F_{SC} can be seen to be very close to 1. The results for the combined slip line are set out in table 1, the pull-out forces in the passive zone being those of table 2. The result obtained for F_{SC}, very close to 1, shows that determination of the slip line by photographic analysis and calculation of the stability against failure are satisfactory.

Another stability calculation was made, not on the observed slip line but for the slip line that is theoretically the most critical. The results are very similar.

Case 2P: $\beta = 60°$, combined slip line, observed line, $F_{SC} = 1.00$ - theoretical line $F_{SC} = 0.99$

Case 3P: $\beta = 60°$, combined slip line, observed line, $F_{SC} = 0.99$ - theoretical line $F_{SC} = 0.95$

The chosen approach is considered to be valid.

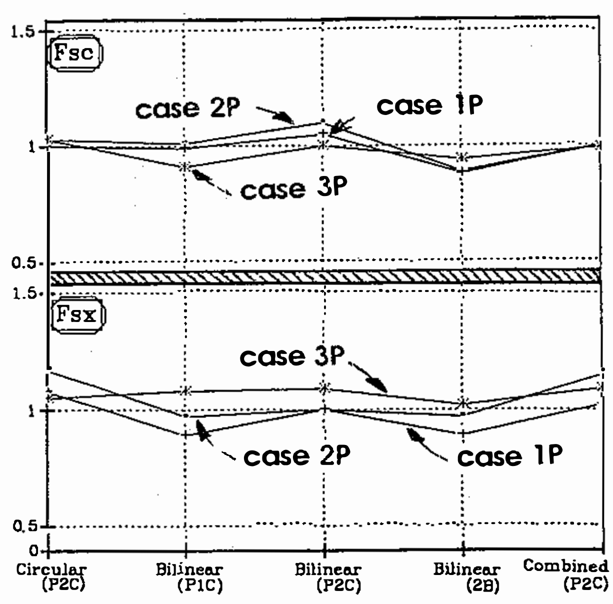


figure 3 : Safety factors F_{SC} and F_{SX} for the different selected slip lines (cases : 1P, 2P, 3P, table 1)

4.1.2 Cellulose paper reinforcement

The density of reinforcement sheets increases from case 1P to case 3P. Efficiency of the reinforcement is expressed as the maximum height H_{max} before failure.

Efficiency of the additional sheets towards the base of the structure is demonstrated (figure 4 and table 1): H_{max} = 49 cm (2P) and 63 cm (3P), where the density at the base is doubled.

On the other hand, reinforcement sheets placed towards the top of the structure do not contribute to stability: H_{max} =49 cm for (1P) and (2P), provided that in case (1P) the maximum height for stability of the cellular facing without reinforcement is not exceeded (H'_{max} = 25 cm - table 3).

Figure 5 shows a photograph of failure with an intermediate density of cellulose reinforcement sheets between (2P) and (3P).

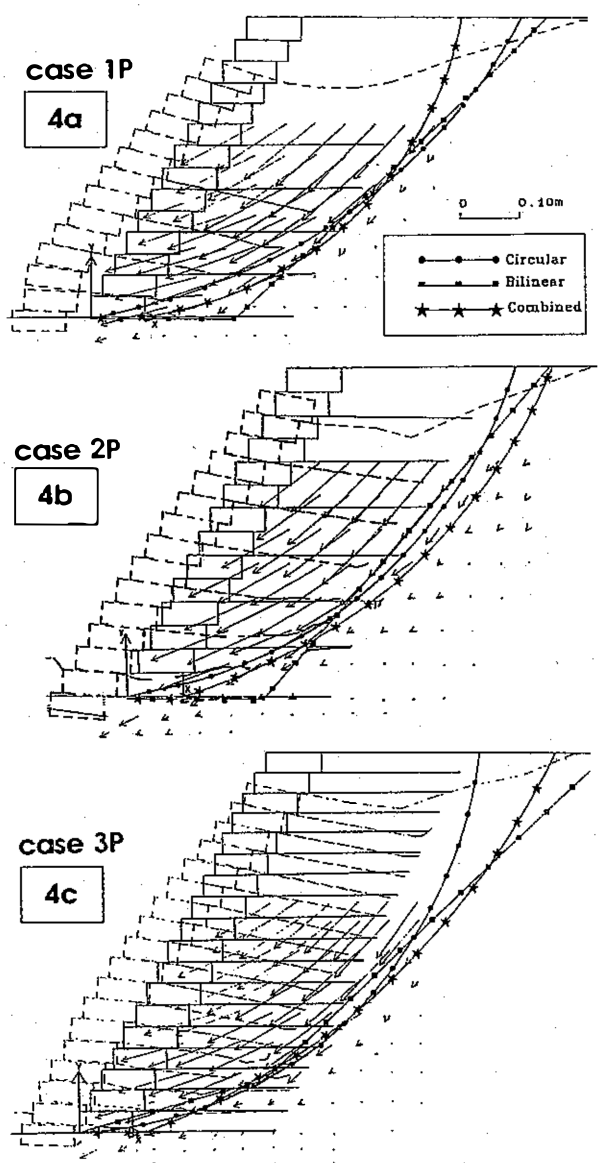
4.1.3 Geotextile reinforcement sheets

Cases (2G) and (3G) are analogous to cases (2P) and (3P). There is no effect in increasing the armouring density: H_{max} = 70 cm (2G) and 71 cm (3G), since the slip line does not here intersect the reinforcement sheets, and encloses the entire reinforced soil embankment (figure 4).

Performance of the stronger reinforcements is demonstrated, for with the same armouring density, H_{max} (geotextile) > H_{max} (cellulose).

4.2 Influence of the cell/soil link

As indicated above, the maximum height of the cellular facing is H_{max} = 25 cm, for β = 60°. If the cell/reinforcement sheet link is severed, failure of the cellular facing is obtained before that of the reinforced soil retaining embankment (table 3 and figure 6: H_{max} = 30cm). For the same density of reinforcement sheets, now linked to the facing, improved performance is obtained: H_{max} = 49 cm (case 2P, figure 4).



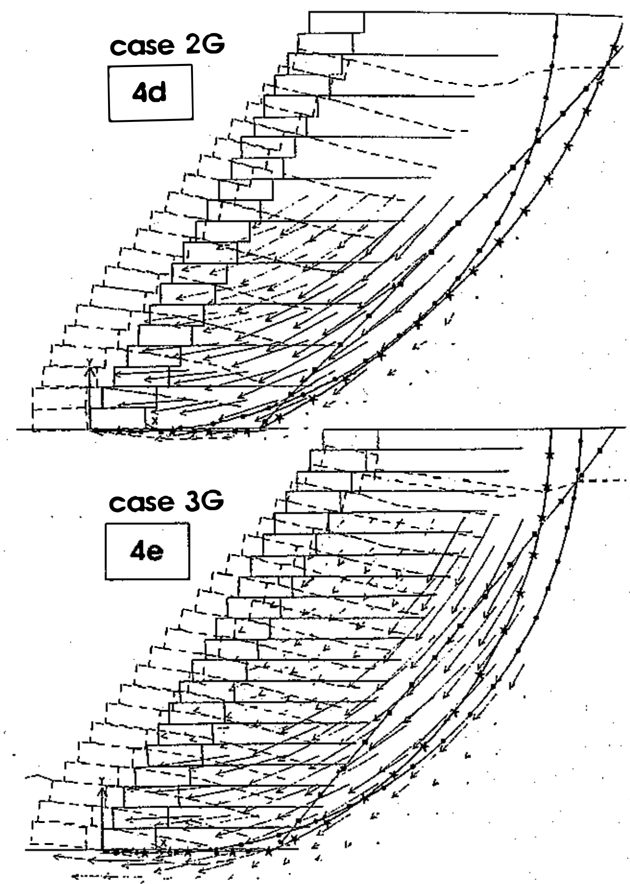


figure 4: Failure of the reinforced soil mass. Influence of the density of reinforcement (cases, table 1)

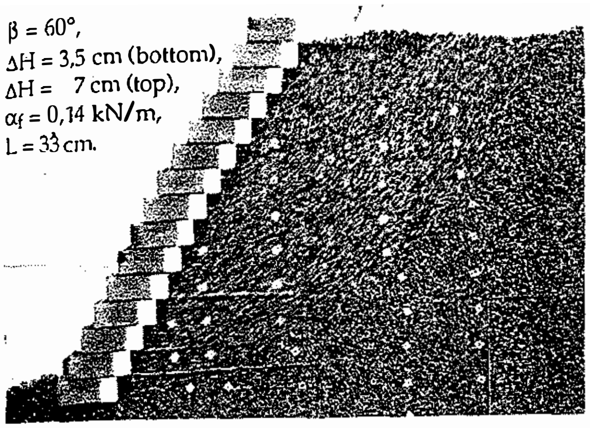


figure 5 : Picture of the reinforced soil mass during the failure

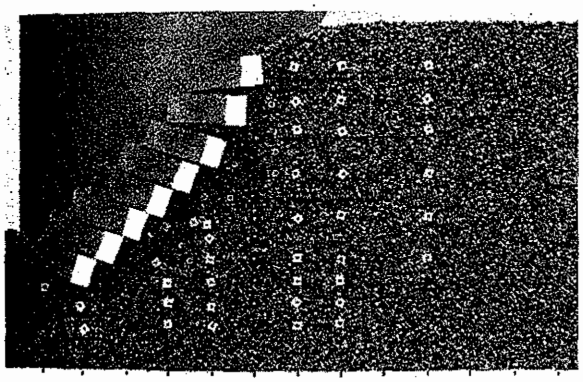


figure 6 : Typical failure of the reinforced cellular facing (without link between cells and sheets : $\beta = 60°$)

Table 3 : Influence of the reinforcement sheets on the stability of the cellular wall ($\beta = 60°$)
F_{SC} for combined slip lines.

link	Hmax (cm)	F_{SC}
linked	49	1,00
no linked	30	0,998
unreinforced	25	0,96

Even if this effect of the link is accentuated by the characteristics of the soil used on the model, the importance of this link to stability of the overall structure is highlighted.

4.3 Influence of length of reinforcement sheets

Two facing techniques are envisaged: a cellular facing and a geotextile facing (figure 7- table 4).

For the same geotextile armouring length L, the results with the two types of facing are relatively close, although there is a slight advantage for the

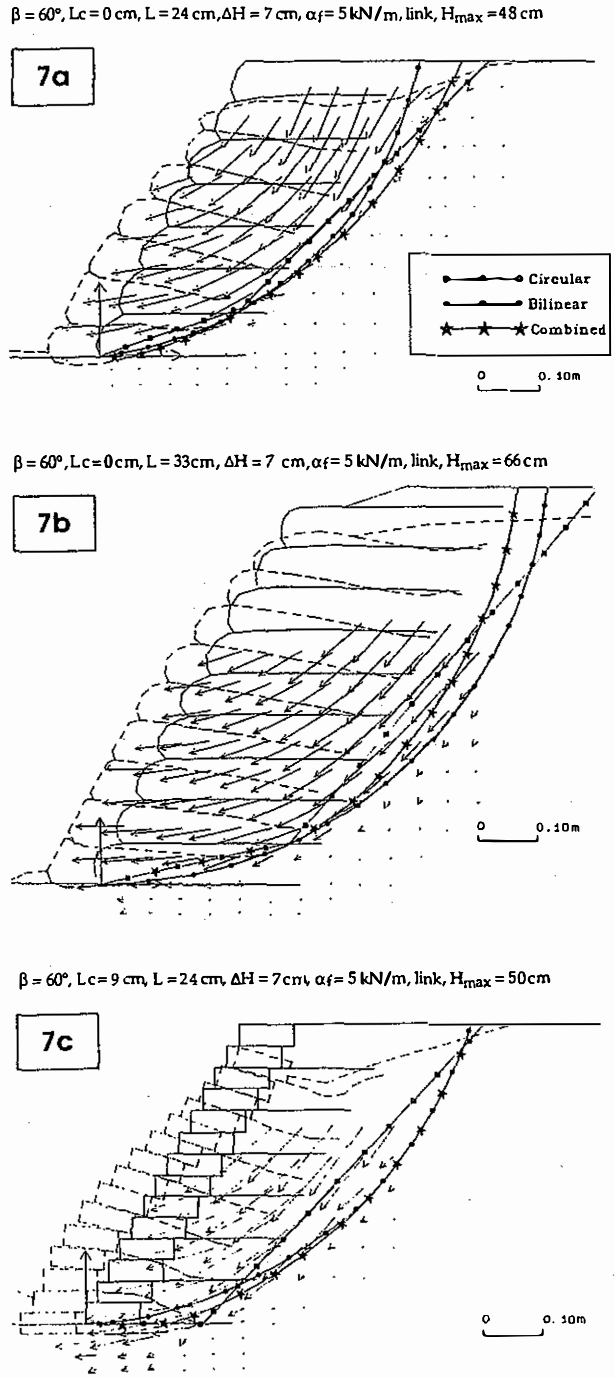


figure 7 : Failure of the reinforced soil mass. Influence of the reinforcement sheet length L for the two facing techniques.

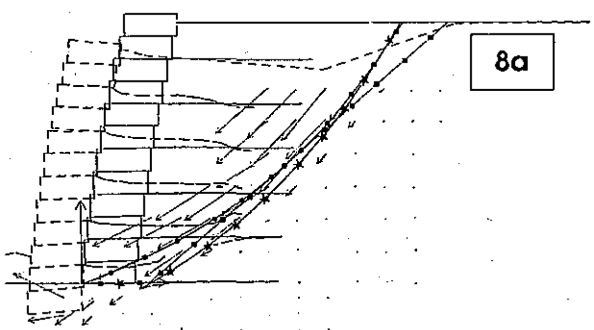
cellular facing regarding the H_{max} value.

For both types of facing, the ratio L/H_{max} is shown to be independent of L, which corresponds to a mode of failure that is virtually external to the retaining reinforced soil embankment itself.

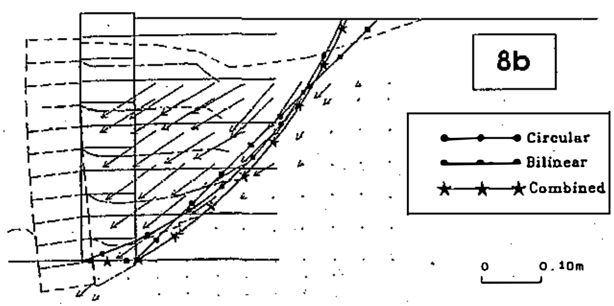
4.4 Influence of facing technique

A cellular facing shows a gain in stability compared to a geotextile facing. Table 5 presents a more precise estimation of the stability gain (H_{max} = 70 cm instead of 66 cm), with the same β and L values, or of the saving on reinforcement length (L = 32 cm instead of 33 cm), with the same β and H_{max} values.

β= 80°, Lc= 9 cm, L =33 cm, ΔH = 7 cm, α_f= 0,14 kN/m, link, H_{max}=42 cm



β= 90°, Lc= 9 cm, L =33 cm, ΔH= 7cm, α_f= 0,14 kN/m, link, H_{max}=39 cm



β = 80°, Lc = 9 cm, L =33cm, ΔH= 7 cm, α_f = 5 kN/m, link, H_{max} = 61 cm

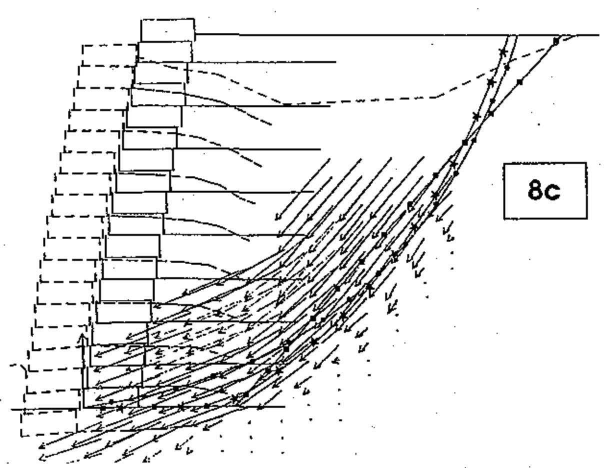


Table 4 : Influence of the length of the reinforcement sheets for the two facing techniques
F_{SC} for combined slip lines.

	Facing geotextile			Facing cells		
L (cm)	Hmax (cm)	L/H	F_{SC}	Hmax (cm)	L/H	F_{SC}
24	48	0,50	0,95	50	0,48	1,20
33	66	0,50	0,84	70	0,47	0,90

Table 5 : Reduction of the length of the reinforcement sheets induce by the cellular facing

Facing	Hmax (cm)	L (cm)
cells	62	30
	64	31,5
	66,5	32
	70	30
geotextile	66	33

Table 6 : Influence of the slope angle β and the tensile strength α_f for the cellular facing model
F_{SC} for combined slip lines.

	β = 60°		β = 80°		β = 90°	
α_f (kN/ml)	Hmax (cm)	F_{SC}	Hmax (cm)	F_{SC}	Hmax (cm)	F_{SC}
0,14	49	1	42	1	39	1,11
5	70	0,94	61	1,39	50	1,37

4.5 Influence of facing slope

Three facing slopes β are considered, for the two types of reinforcement, cellulose and geotextile, with the same length L = 33 cm.

The maximum height obtained decreases as the slope angle β increases (table 6).

β= 90°, Lc = 9 cm, L =33 cm, ΔH = 7cm, α_f=5 kN/m, link, H_{max} = 50cm

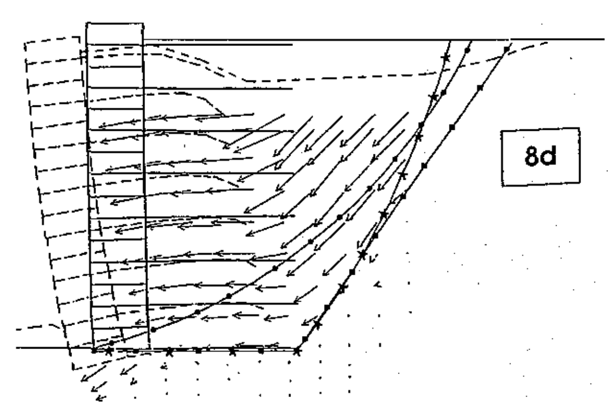


figure 8 : Failure of the reinforced soil mass. Influence of the slope angle β and of the tensile strength α_f of the reinforcement.

It can be seen (figure 8) that the kinematic conditions of failure change with β. For embankments with steeper slopes β, tilting of the facing and the reinforced soil mass, possibly associated with compaction settlement of the foundation soil, is superimposed on the sliding phenomenon. This is particularly evident in the case of the geotextile-reinforced structure (figure 8). In this case, the sliding safety coefficient F_{SC} obtained is well over 1, where the failure has occurred "prematurely" due to a failure mode other than sliding. A complementary study is envisaged to research this aspect.

5. CONCLUSION

Experiments on the two-dimensional scale model proved valuable for obtaining a better understanding of the conditions of instability of soil structures reinforced by horizontal sheeting. They also open a debate on the equilibrium limit calculation methods that are conventionally applied to this type of structure.

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