EROSION CONTROL :The Design with TENAX TENWEB geocells

Rimoldi Pietro, Tenax SpA
Ricciuti Angelo, Tenax SpA
Recalcati Piergiorgio, Tenax SpA

1. Introduction

The growing attention to the problems of Environment Impact has allowed a fast development of the geosynthetics used for erosion control and revegetation of arid areas, slopes, road embankments, etc.

Erosion has always been one of the major sources of damage to both the natural environment and the man-made structures.

Erosion is caused by different factors and can be avoided only if protection measures are properly selected according to its cause. Erosion on slopes may be caused by rainfall, runoff or wind. Rainfall erosion occurs mainly on bare slopes, while the vegetation provides the natural and best protection: in fact the rainfall erosion is caused by the splash of the rain drops which detaches and displaces the soil particles, making them available for transport by gravity and surface runoff.

A dense vegetation cover both absorbs the impact energy of the rain drops and ties the surface soil granules through the roots network. Hence, the best way to protect a slope from this kind of erosion is to establish quickly a dense and uniform grass cover.

Geomats are purposely engineered for trapping a layer of topsoil, thus avoiding rainfall erosion by both sheltering the surface against the raindrops impact and by reducing the movement of the soil particles.

The stability of the surface layer of topsoil allows the seeds to germinate quickly and the vegetation to uniformly cover the slope. While growing, the roots intertwine with the geomats, thus creating a natural-synthetic network with a much higher resistance to the shear forces than the roots alone.

When the surface is intersected by a high surface runoff, the erosion takes place progressively: initially the runoff is in the form of sheet flow and it mainly transports the soil detached by the rainfall; then preferential paths for the water flow appear and the runoff starts to excavate rills; this channeled flow greatly increases the local water speed and its erosivity: as a consequence the rills quickly degenerate into deep and wide gullies. The latest stage of the erosion may take the form of small soil failures and even of landslides.

The best protection against erosion is provided by geosynthetics: small slopes can be effectively protected with geomats, while areas with long slopes and/or high runoff may require the use of geocells. Geocells are geosynthetics whose main function is soil confinement. Geocells stabilise

the soil or aggregate infilled by providing lateral confinement: in this situation the infiltration of the water is facilitated and the runoff is decreased both in volume and in speed, with a consequent reduction of the water erosivity. Rills and gullies are therefore prevented.
The combined use of geocells, for stabilising a thick topsoil layer, and of geomats, for surface protection, provides the most effective erosion control system in heavy situations.

2. Designing with TENAX TENWEB geocells.

Geocells are nowadays widely used for erosion control on slopes. In many cases the soil of a slope is rocky or totally arid, due to the lack of organic materials in the soil matrix. This situation often occurs when cutting a road slope, or in quarry areas or generally in rather dry regions. In this condition a minimum top soil layer of 70-100 mm is required to be laid on the arid soil for the vegetation to be successfully established on the slope. But top soil has low geotechnical characteristics and can easily slip down along slopes with an inclination greater than 30°, or it can be deeply eroded by heavy or sustained rains occurring prior to grass growth.
Geocells provide stability to the top soil layer through confinement: once extended to their full open size and filled with lightly compacted top soil, a stable and inextensible planting medium is achieved. Slopes with different length, inclination, soil characteristics, can be properly protected against erosion by the choice of the most suitable kind of geocells.
TENAX TENWEB geocells have junctions that allow the passage of water between adjacent cells. All the cells are hydraulically connected and the composite structure presents good permeability. During the advent of precipitation, this particular structure facilitates water infiltration into the soil, thus reducing runoff and decreasing erosion.
The aim of this chapter is to provide the criteria for the selection of the suitable type of TENAX TENWEB geocells for a given slope. Then the total active and resisting forces are compared to calculate the factor of safety against sliding along the slope. The stability analysis is also performed for the top block, which act as an anchorage element for the central block along the slope, and the block at the toe of the slope, which act as a passive wedge. The suggested design procedure allows to take into account the application of the geocells both on a soil slope and on a slope waterproofed with a smooth geomembrane. This latter case cover the use of geocells for the capping of landfills and for other common applications. The design method considers the resistance of the junctions of the geocells and allows to determine the number of pegs/staples required to anchor the geocells to the ground without junctions failure. In case of use of the geocells on a smooth geomembrane, a geogrid is placed between geocells and geomembrane: the design method allows to determine the long term strength required for the geogrid. The design

method presented in the paper is therefore based on theoretical considerations, laboratory tests and field experience of the modes of failure.

2.1 Stability analysis

The choice of the most suitable kind of geocells comes from stability analysis. As follows the stability analyses are performed for the central block, the top block and the block at the toe of the slope.

2.1.1 Stability analysis along the slope

The design parameters, to determine the active sliding forces and the resistant forces, are the following:

t = depth of geocell, [m];
t_s = soil thickness, [m];
t_t = trench depth, [m];
β = slope angle, [°];
L = slope length, [m];
γ = saturated unit weight of fill soil, [kN/m^3];
ϕ_s = friction angle of subsoil, [°];
ϕ_f = friction angle of fill soil, [°];
ϕ = interface friction angle between fill soil and subsoil, [°];
c = cohesion of the fill soil.
ϕ_t = friction angle of the soil in the top trench [°];
γ_t = unit weight of the soil in the top trench, [kN/m^3];

Usually, the cohesion of the fill soil is neglected because it is very difficult to evaluate it.

The variables are
l = spacing of the fixing pins, [m];
b = number of fixing pins or stakes per unit width, [m^{-1}];
L_a = the anchorage length at the crest, [m].
The first stability analysis is performed for the central block. The knowledge of the design parameters allows to determine the forces which will govern the design.
The weight of the cellular confinement system filled by soil is:

$$W = \gamma \cdot L \cdot t_s \tag{1}$$

while the sliding force is:

$$F_s = W \cdot \sin\beta \tag{2}$$

The global resisting force R_{tot} will be calculated as the sum of:

$$R_{tot} = S + R_{crest} / FS_j + R_j / FS_j + R_g + P_p + R_c \tag{3}$$

where:

$$S = \gamma \cdot L \cdot t_s \cdot \cos\beta \cdot \tan\phi \tag{4}$$

is the frictional resistance along the slope;

$$R_{crest} = n_j \cdot J_{\min} \tag{5}$$

is the resistance due to the junction strength with

n_j = number of junctions per m;

J_{min} = minimum junction strength.

This strength must be evaluated by means of specific tests. Typical tests are: shear (one strip is displaced relatively to the adjacent strip along the direction of the strips themselves); peeling (one strip is displaced relative to the adjacent strip, perpendicular to the direction of the strips themselves); splitting (two of the four convergent strips in the junction are stretched relative to the other two, perpendicular to the junctions). CEN test ..... provides the standard for the evaluation of the junction strength of geocells.

$$R_p = b \cdot J_p \tag{6}$$

is the additional resisting force provided by transferring the slope load through the fixing pins, with

J_p = shear strength of geocell junction under the stress applied by pins, [kN].

b = number of pins per run meter of slope, [m^{-1}];

As pins are placed in staggered pattern (see installation procedure), if the pins spacing (horizontal and vertical) is l and the length of the slope is L:

$$b = \frac{2}{l^2} \cdot L \qquad (7)$$

R_g is the tensile strength of the geogrid at 2% of elongation. The use of the geogrid shall be necessary when the slope is steep or when there is a geomembrane at the interface with consequent reduction of the friction angle.

$$P_p = 1/2 \cdot K_p \cdot t_s{}^2 = 1/2 \cdot \tan^2(45° + \phi/2) \cdot t_s{}^2 \qquad (8)$$

is the passive strength provided by adjacent cells at the toe of the slope.

$$R_c = c \cdot L \qquad (9)$$

is the resistance along the slope due to cohesion of the infill soil.

FS_j is the factor of safety against junction failure; it should have a minimum value of 1.5.
The global factor of safety, FS, shall be calculated as the ratio between the resisting forces and the sliding force:

$$FS = R_{tot} / FS \qquad (10)$$

The value of FS depends upon the importance of the project, and should have a minimum value of 1.3.

2.1.2 Stability analysis of the anchorage block at the crest

The stability analysis along the slope allows the selection of the suitable product and the calculation of the spacing between pins. Stability analysis of the anchorage block allows to determine the width of the trench by fixing its height.

The factor of safety for the anchorage block shall be:

$$FS_a = S_a / (F_s - S - R_c) \cdot \cos\beta \qquad (11)$$

S_a is the horizontal component of the resisting force provided by the trench:

$$S_a = \gamma_t \cdot t_t \cdot L_a \cdot \tan\phi_t \quad (12)$$

with

L_a = anchorage length;

t_t = trench height;

ϕ_t = trench fill friction angle;

γ_t = trench fill unit weight.

At the denominator the sliding force is reduced by the frictional resistance. The contribution of the junction strength is neglected for sake of safety.

Anyway L_a should have a minimum value of 0.75 m.

2.1.3 Stability analysis at the toe

The factor of safety is:

$$FS_t = S_t / P_p \quad (13)$$

where:

$$S_t = \gamma \cdot t_s \cdot L_t \tan\phi \quad (14)$$

with L_t, anchorage length at the toe.

Anyway L_t should have a minimum value of 1.0 m.

2.1.4 Stability analysis for the topsoil

In particular circumstances, the thickness of the soil is greater than the cells thickness. In this case we have to verify the stability of the soil on the geocells.

The sliding force given by the soil upon the cells is:

$$F_{s1} = L \cdot (t_s - t) \quad (15)$$

with

t_s = total thickness of the soil.

The total resistant force shall be:

$$R_{tot1} = S_1 + P_{p1} + R_{g1} + R_c \tag{16}$$

where:

$$S_1 = (t_s - t) \cdot L \cdot \cos\beta \cdot \tan\phi \tag{17}$$

$$P_p = 1/2 \cdot \tan^2(45° + \phi / 2) \cdot (t_s - t)^2 \tag{18}$$

$$R_c = c \cdot L \tag{19}$$

R_{g1} is the tensile strength of the geogrid necessary to increase the resistant forces.
The factor of safety shall be:

$$FS_1 = R_{tot1} / F_{s1} \tag{20}$$

and it should have a minimum value of 1.3.

2.2 Worked examples

Example 1.

It is required to allow grass vegetation over the slopes of a railway embankment; the embankment is made with arid soil (gravel).

Geometry of the slope:

Slope angle:	β = 33.69° (V/H=2/3);
Slope length	L = 8.00 m;
Friction angle of the slope soil:	ϕ_s = 35°
Friction angle of the fill soil:	ϕ_t = 25°
Friction angle at the interface:	ϕ = 25°

Unit weight of the fill soil: γ = 15.00 kN/m³;

Friction angle of the trench soil: ϕ_t= 35°

Unit weight of the trench soil γ_t= 19.00 kN/m³;

(it is possible to fill the trench with gravel)

Undrained cohesion of the fill soil: c = 0 kPa

To allow a proper growth of the grass it is required a minimum of 100 mm top soil; thus, it is necessary to choose TENWEB panels with

Panel thickness = soil thickness $t = t_s$ = 0.10 m.

The following Factor of Safety are required:

FS_{global}	1.50
$FS_{anchorage}$	1.50
FS_{toe}	1.50
$FS_{junction}$	2.00

We do the hypothesys to use TENWEB 4/300 characterized by:

Junction tensile resistance	J_p	= 0.80	kN
Peel resistance	J_{min}	= 0.35	kN
Peak tensile strength	J_{max}	= 1.20	kN
Number of junction	$N_{junction}$	= 3	junct/m

Furthermore, we suppose to use 1 pin/0.90 m (in staggered pattern), that is:

Number of pins b = 19.75 (19) pin/1 running m

Global stability analysis:

From equation (1), the weight of the of the soil confined in the cells is

W = 12.00 kN/m

while the sliding force (2) is

F_s = 6.66 kN/m

The resisting forces, expressed by eq. (4 - 9), have the following values:

S = 4.66 kN/m

C = 0.00 kN/m

R_{g1} = 0.00 kN/m

P_p = 0.18 kN/m

$R_j / FS_{junction}$ = 7.60 kN/m

$R_{crest} / FS_{junction}$ = 0.53 kN/m

From eq. (3) and (10), we have:

R_{tot} = 12.97 kN/m;

FS = R_{tot} / F_s = 1.94 (>1.50)

Stability at crest:

Form eq. (11-12), imposing FS_a = 1.50, we have:

$L_a = FS_a (F_s - S - R_c) \cos\beta / (\gamma_t t_t \tan\phi_t)$ = 0.38 m < 0.75 m

We impose

L_a = 0.75 m

Stability at toe

From eq. (13-14), imposing FS_t=1.50, we have:

$L_t = FS_t P_p / (\gamma t_s \tan\phi)$ = 0.38 m < 1.00 m

We impose

L_t = 1.00 m

Example 2:

With the same geometry and soil characteristics, it is required to have a minimum of 0.20 m vegetal soil thickness (t_s = 0.20 m).

We do the hypothesys to use TENWEB 4/200 characterized by:

Junction tensile resistance	J_p	= 0.80	kN
Peel resistance	J_{min}	= 0.35	kN
Peak tensile strength	J_{max}	= 1.20	kN
Number of junction	$N_{junction}$	= 5	junct/m

Furthermore, we suppose to use 1 pin / 0.80 m (in staggered pattern), that is:

Number of pins	b	= 25	pin/1 running m

Slope stability:

From equation (1), the weight of the of the soil confined in the cells is

W = 24.00 kN/m

while the sliding force (2) is

F_s = 13.31 kN/m

The resisting forces, expressed by eq. (4 - 9), have the following values:

S = 9.31 kN/m

C = 0.00 kN/m

R_{g1} = 0.00 kN/m

P_p = 0.74 kN/m

R_j / $FS_{junction}$ =10.00 kN/m

R_{crest} / $FS_{junction}$ = 0.88 kN/m

From eq. (3) and (10), we have:

R_{tot} = 20.93 kN/m

FS = 1.57 > 1.50

Stability at crest:

From eq. (11-12), imposing FS_a = 1.50, we have:

$L_a = FS_a (F_s - S - R_c) \cos\beta / (\gamma_t\, t_t\, \tan\phi_t) = 0.75$ m

Stability at toe:

From eq. (13-14), imposing FS_t=1.50, we have:

$L_t = FS_t\, P_p / (\gamma\, t_s \tan\phi) = 0.79$ m < 1.00 m

We impose

L_t = 1.00 m

Stability upon TENWEB

As $t_s > t$, it is necessary to verify also the stability of the soil upon TENWEB; obviously, being c=0 and $\phi<\beta$, the FS_1 for the topsoil will be < 1.00. Therefore, it is necessary to add a geogrid upon TENWEB to stabilize the soil.

From eq. (15), the sliding force F_{s1} is

F_{s1} = 6.66 kN/m

Form eq. (16-19), the resisting forces are given by:

S_1 = 4.58 kN/m

R_{c1} = 0.00 kN/m

P_{p1} = 0.28 kN/m

R_{tot1} = 4.86 kN/m

to reach the required FS1 = 1.30, it is necessary to provide a tensile strength equal to

$R_{g2} = F_{s1}\, 1.30 - R_{tot1} = 3.79$ kN/m

Considering the tensile strength at 2% strain, it is possible to use a bi-oriented geogrid type TENAX LBO 201 SAMP, with a $R_{2\%\ strain}$ = 4.50 kN/m in MD.

Example 3:

It is required to vegetate the slopes of a channel. The channel is waterproofed with a smooth HDPE geomembrane. As there is no need to vegetate the bottom of the channel, the toe cells will be filled with the same soil used in the anchorage trench.

Geometry of the slope:

Slope angle:	β = 45°;
Slope length	L = 4.00 m;
Friction angle of the slope soil:	ϕ = 0°
Friction angle of the fill soil:	ϕ = 25°
Friction angle at the interface:	ϕ = 0°
Unit weight of the fill soil:	γ = 15.00 kN/m³;
Friction angle of the trench soil:	ϕ_t= 35°
Unit weight of the trench:	γ_t = 19.00 kN/m³;

(it is possible to fill the trench with gravel)

Undrained cohesion of the fill soil: c = 0 kPa

It is required a minimum of 75 mm top soil; thus, it is necessary to choose TENWEB panels with

Panel thickness = soil thickness $t = t_s$ = 0.075 m.

The following Factor of Safety are required:

FS_{global}	1.50
$FS_{anchorage}$	1.50
FS_{toe}	1.50
$FS_{junction}$	2.00

We do the hypothesys to use TENWEB 3/100 characterized by:

Junction tensile resistance	J_p	= 0.80	kN
Peel resistance	J_{min}	= 0.35	kN
Peak tensile strength	J_{max}	= 1.20	kN
Number of junction	$N_{junction}$	= 8	junct/m

Obviously, in this case it is not possible to use pin (as it would be necessary to hole the geomembrane).

Global stability analysis:

From equation (1), the weight of the of the soil confined in the cells is

W = 5.06 kN/m

while the sliding force (2) is

F_s = 3.58 kN/m

The resisting forces, expressed by eq. (4 - 9), have the following values:

S = 0.00 kN/m

C = 0.00 kN/m

$R_{g1} = 0.00$ kN/m

$P_p = 0.04$ kN/m

$R_j / FS_{junction} = 0.00$ kN/m

$R_{crest} / FS_{junction} = 1.40$ kN/m

From eq. (3) and (10), we have:

$R_{tot} = 1.44$ kN/m

$FS = 0.40 < 1.50$.

It is necessary to add a geogrid beneath TENWEB. The minimum required 2% strain of the geogrid is given by

$R_{g1}=F_s\ FS - R_{tot} = 3.58\ 1.50 - 1.44 = 3.93$ kN/m

It is possible to use a bi-oriented geogrid type TENAX LBO 201 SAMP, with a $R_{2\%\ strain} = 4.50$ kN/m in MD.

Stability at crest:

From eq. (11-12), imposing $FS_a = 1.50$, we have:

$L_a = FS_a\ (F_s - S - R_c) \cos\beta / (\gamma_t\ t_t\ \tan\phi_t) = 0.57$ m < 0.75 m.

We impose $L_a = 0.75$ m

Stability at toe:

From eq. (13-14), imposing $FS_t=1.50$, we have:

$L_t = FS_t\ P_p / (\gamma_t\ t\ \tan\phi_t) = 0.06$ m < 1.00 m

We impose $L_t=1.00$ m

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TENAX TENWEB INSTALLATION PROCEDURE

The installation of TENAX TENWEB geocells on slopes is relatively simple and can be easily performed by unskilled labourers. The procedure is as follows:

Site preparation

Clear and grub the site. Site should be brought up to grade as specified by designer. The surface should be as smooth as possible.

Placement of the geocell panels

Geocell panels shall be expanded to the full open dimension, parallel to the flow direction. Each panel shall be first anchored at the top of the slope in a trench whose dimensions are determined by design. If it is possible, the anchorage trench at the top can be filled with concrete (to reduce the embedded length).

Along the slope the geocells shall be anchored with pins. The spacing between the pins shall be determined by the design engineer.

Pins have shape and length depending on the soil characteristics. Pin diameter shall be 8 mm minimum.

Each pin shall be placed at the junctions of the panel (See drawing).

Pins are placed in staggerd pattern, that is like the number 5 on a die (See drawing).

Junction between panels

Adjacent panels shall be fixed by pins, one pin each cell (see drawing).

Infill

Infill in the geocells is influenced by hydraulics, soil conditions, aesthetics. The geocells can accommodate infills and finishes such as soil/grass, gravel.

Infill can be placed by the use of a front endloader, backhoe, bottom dump bucket, conveyor system or ready mix truck. Soil or granular infill material shall be about 2 cm above the top of the cells and compacted to the required density.

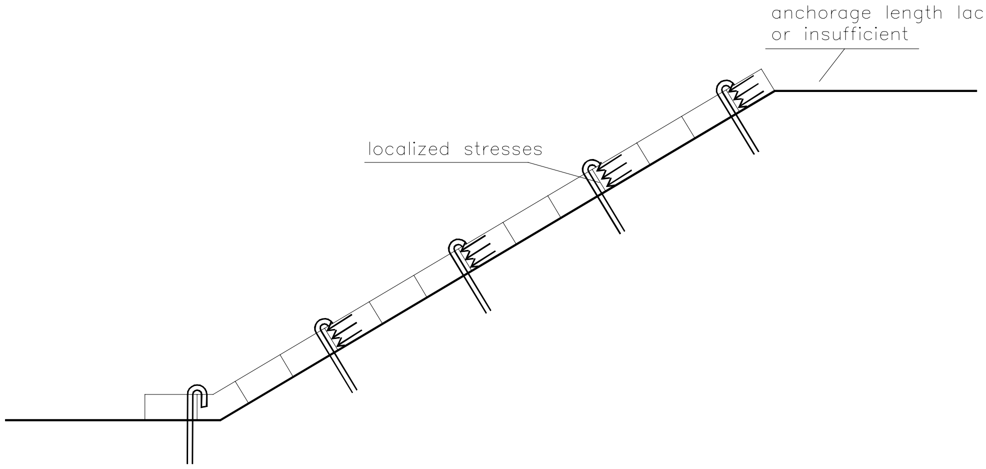
Finishing details

Seeding with suitable essences allows a fast vegetation. Seeded areas may be protected with synthetic or natural fibre blankets (jute).

Particular considerations

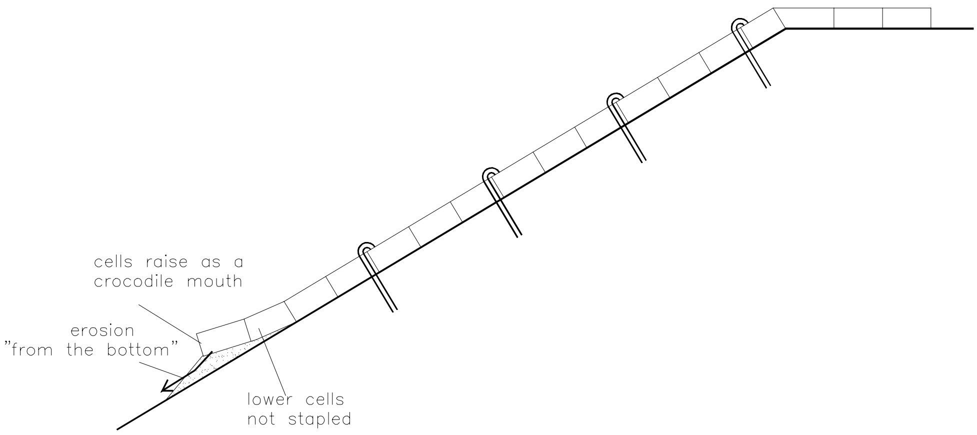
Anchorage at top

If it is not possible to provide a proper anchorage at top, or if the anchorage length is not sufficient, the geocells panel begin to slide downward; the only resistance is given by the fixing pins. Localised stresses transmitted by the pins to the junctions (particularly the upper cell junctions) may plasticize (and break) the junctions. The surrounding cells then open, thus reducing soil confinement; then localised erosion may occur. This can be avoided by increasing the number of pin when the anchorage length is insufficient.



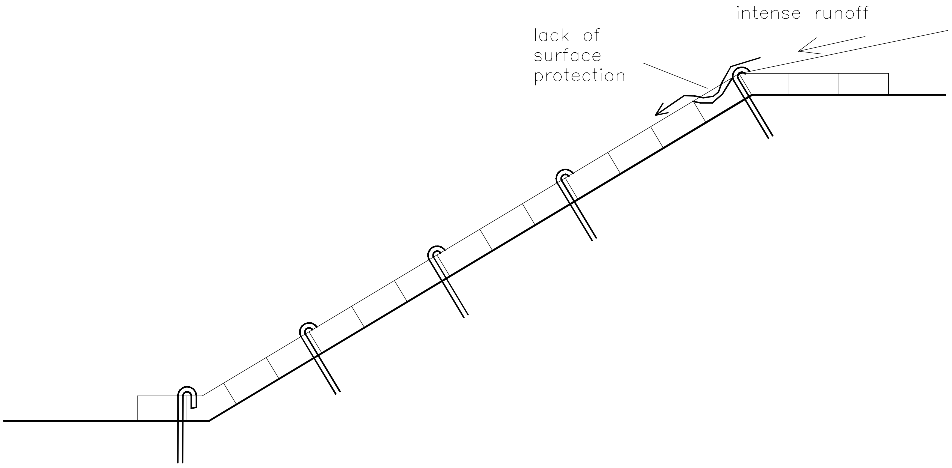
Anchorage at toe

It is important to fix carefully the lower cells (in a base trench or by pins). When this is not properly done, the lower cells row may raise in “crocodile mouth shape”. Infiltration water, passing through the cells apertures, will then empty the cells from the bottom. When the first row of cells is empty, the second one begins to raise, and so on. Erosion continues up to the first pin, able to avoid cell raise. Obviously, if the first row of cells is properly fixed, the problem will not occur.



Intense runoff

If there is a long slope upstream, or there is any possible cause of intense runoff, the top rows can be subject to intense erosion. The change of slope angle, in fact, causes a local increase in water flow speed. To avoid the consequent erosion, it is necessary to cover the zone with a bio-mat or, better, with a geomat. It is strongly recommended to excavate a draining ditch immediately upstream the surface to be protected, thus reducing the runoff.



Lack of pins

Finally, if the number of pins is less than required or if the pins used are not properly chosen, the localised stress transmitted by pins to the junctions can break them. The failure of a junction transmits an over-stress to the adjacent junction, thus producing a progressive failure. It is therefore important to verify with laboratory tests the junction strength, depending upon the kind of pins used (Montanelli e Rimoldi, 1994, give details on the tests on geocell junction).