Geosynthetics: Applications, Design and Construction, De Groot, Den Hoedt & Termaat (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 836 3

Green faced reinforced soil walls and steep slopes: The state-of-the-art in Europe

Pietro Rimoldi
Tenax SpA, Viganò (LC), Italy
Felix Jaecklin
Geotechnikbüro, Ennetbaden, Switzerland

ABSTRACT: Green faced geosynthetic reinforced soil structures are introduced and presented. Main applications are shown. Design methods and criteria are explained. Construction schemes and installations techniques are illustrated. The main properties of reinforcing geosynthetics are listed, together with the appropriate laboratory tests to evaluate them. Several design softwares are compared. The need for harmonization is stressed.

1 INTRODUCTION

The use of geosynthetics for building reinforced soil slopes and walls has come to an advanced stage of development, becoming a subject of main economical importance in the "geotechnical business".

Some European countries have led the way to the present development of vegetated reinforced soil structures, while USA and Japan concentrated more on concrete faced walls.

In fact, several proprietary systems are now existing for the construction of vegetated reinforced soil walls and slopes, and almost all of them come from European countries.

Reinforced soil is a general term which encompasses all the construction methods, but peculiar techniques are required for obtaining a vegetated face, which are not required for a concrete faced structure. Therefore this paper concentrates only on the design and construction techniques which are typical of reinforced soil slopes and walls with vegetated face.

Reinforced soil is a composite material that combines the typical resistance of two different materials in such a way to improve the mechnical characteristics of each one. Particularly, a relatively large quantity of the cheapest and compression resistant material, the soil, is improved in its engineering characteristics by the combination with a relatively small quantity of a more expensive and highly tensile resistant material. Therefore a synergy is developed between the tensile and compressive resistance of the two materials: this sinergy improves the global characteristics of the composite material, like with concrete and steel.

The reinforced soil concept is thousands of years old, and has experienced different types of reinforcing materials, from bamboo to tree branches, from steel strips to geosynthetics (Jones, 1985; Giroud 1986). The modern development of reinforced soil started with the "Terre Armée" walls, invented by Henry Vidal and originally patented in France in the early sixties. The principle was to use galvanized steel strips placed in a fill and attached to a front facing; at first it was an aluminium cover, later precast concrete cross shaped panels. Extensive marketing and sound contracting of "Reinforced Earth" brought it to a world-wide success never matched before by any other product nor construction method in the foundation or earthwork industry. The method, which has already experienced many variations, is widely used in US and Western Europe and many technical codes include the specifications of the "Reinforced Earth" system.

Geotextile and geogrid reinforced walls could become successful very quickly because of the existence and the widespread acceptance of such other system using tension members embedded into the backfill mass, producing a soil-reinforcement interaction which allows the combined material to exceed by far the stability behaviour of the soil alone.

Not surprisingly the methods of construction are still similar and in use over 30 years later; moreover the design calculation methods are, still today, using classical design approaches with slip circles or block sliding. Anyway the principle of "homogenisation" is well known and it has been clearly demonstrated (Schlosser et Al., 1983) that the combination of soil and tensile inclusions produce a new "composite" material of superior characteristics than the components. But the homogenisation technique has not produced so far internationally accepted design methods and therefore almost the same methods applicable to the design of anchored excavated slopes are applied also for polymer reinforced soil fills.

2 TERMINOLOGY

"Geosynthetics" is a general term which identifies a broad range of products, such as geotextiles, geomembranes, geogrids and many others.
The definition of "Geosynthetics" and of each family of products is still under discussion in several Committees around the world.
Here we list our definitions of the reinforcement products, which are based on the latest developments of the international discussion (from Giroud, 1986, to Rimoldi et Al, 1993).

Geosynthetic: a synthetic or natural material in the form of manufactured sheet, strip or panel, used in geotechnical, environmental, hydraulic and transportation engineering applications.

Geogrid: a permeable polymeric structure, unidirectional or bi-directional, in the form of manufactured sheet, consisting of a regular network of integrally connected elements, which may be linked by extrusion, bonding or interlacing, whose openings are usually larger than the constituents, used in geotechnical, environmental, hydraulic and transportation engineering applications.

- Unidirectional geogrid: a geogrid which possesses a much higher tensile strength in one direction (longitudinal or transversal) than in the other direction.
- Bidirectional geogrid: a geogrid which possesses similar tensile strength in both longitudinal and transversal direction.
- Extruded geogrid: a geogrid produced by stretching uniaxially or biaxially an extruded integral structure.
- Bonded geogrid: a geogrid produced by bonding, usually at right angles, two or more sets of strands or other elements.
- Woven geogrid: a geogrid produced by interlacing, usually at right angles, two or more yarns, filaments or other elements.

Geotextile: a permeable, polymeric (synthetic or natural) textile material, in the form of manufactured sheet (which may be woven, non-woven or knitted) used in geotechnical, environmental, hydraulic and transportation engineering applications.

- Woven Geotextile: a geotextile produced by interlacing, usually at right angles, two or more sets of fibres, filaments, tapes or other elements.
- Knitted geotextile: a geotextile produced by interlooping one or more fibres, yarns, filaments or other elements.
- Non-woven geotextile: a geotextile produced by the bonding (by means of friction and/or cohesion and/or adhesion) of directionally or randomly oriented fibres.

Other important definitions are listed here below.

Steep slopes and walls: for a uniform fill soil there is a limiting slope angle β_{lim} to which an unreinforced slope can be safely built.
For the case of non-cohesive and dry material, the limit angle of the slope equals the friction angle of the soil:

$$\beta_{lim} = \phi' \tag{1}$$

A slope with a greater angle than the limit slope angle is a steep slope; to build a steep slope it is necessary to provide some additional forces to maintain equilibrium.
The upper limit to the slope angle is 90°. By a proper selection of the geosynthetic reinforcement and of the construction method, it is possible to build slopes up to vertical, with a vegetated face. Obviously, the steeper the slope gets, the more difficult the grass growth becomes.
Thus, a reinforced soil structure can be defined according to the geometry: a slope with $\beta_{lim} < \beta \leq 70°$ is defined as a steep slope, while a structure with $\beta > 70°$ is defined as a wall (BSI, 1995).

Face support: it is defined as the system used to support temporarily the wall face during the installation and the soil compaction procedures. Reinforced structures can be classified on the base of the face support system, that is on the base of the construction technique. For shallow slopes, no face support is required during construction; steep slopes, or walls, on the contrary, require a face support system. Whichever method is used, the face support system has no structural function.

Face finishing: it is defined as the permanent system used to protect the face of a slope or a wall.

The finishing of a reinforced structure is one of the most important aspects to be considered during design and construction. In fact the soil reinforcing techniques provide the designer with the possibility to build even large soil structures with a very low environmental impact. It is easy to understand that a perfectly vegetated wall can be much more acceptable, from an aesthetic and environmental point of view, than a reinforced concrete wall. Therefore, particular care must be taken by the designer in the selection of the most suitable kind of face finishing. A vertical reinforced wall can be finished with thin concrete panels (full height or segmental), segmental concrete blocks, with gabions or vegetated face. A steep slope can be finished with a vegetated face, gabions, or with shotcrete.

In this paper only green faced reinforced soil structures are presented.

3 PRINCIPLES OF REINFORCED SOIL

A simple model helps to explain the principle on which the reinforced soil techniques are based.
Let us consider a soil element (Fig. 1), which is part of an infinite mass of soil: the application of a vertical stress σ_v produces a deformation in the element and the consequent horizontal stress $\sigma_{h,}$ generated by the lateral compression suffered by the adjacent soil. Horizontally the soil element undergoes a "tensile deformation" ε_h, which is one of the main causes of local failures.

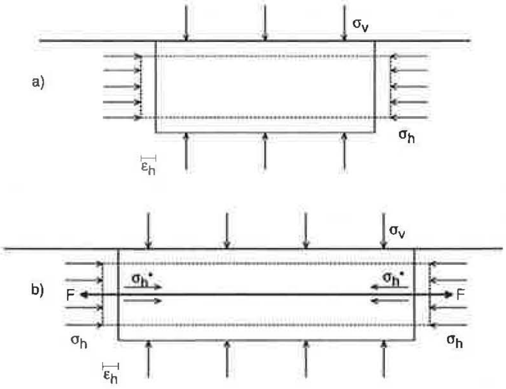

Fig. 1

When a reinforcing element is put into the soil, the application of a vertical stress is followed by the deformation of the soil element and the extension of the reinforcement. This extension then generates a tensile strength T in the reinforcement, which in turn produce a horizontal stress σ_h^*. This stress, which also provides a confinement action on the soil granules, greatly contributes to resist the horizontal forces and to reduce the horizontal deformations. Therefore the inclusion of a geosynthetic into the soil mass reduces the stresses and strains applied to the soil; on the other hand the vertical stress σ_v applied to the soil mass can be increased, compared to the unreinforced soil, at equal deformations. With regards to the resistance to the shear stresses in a non-cohesive soil element we have:

$$\tau_{max} = \sigma \cdot \tan \phi_{max} \qquad (2)$$

where:
ϕ_{max} = maximum angle of shear resistance of soil
τ_{max} = maximum overall shear stress provided by the soil

When the soil element is crossed by a reinforcement element (Fig. 2), which makes a ϑ angle with the shearing direction, the state of stress is modified because the tension T generates a shear stress produced by the tangential component $T \cdot \sin\vartheta$, meanwhile the normal component $T \cdot \cos\vartheta$ generates another $\tau^{\wedge}$ caused by the friction angle ϕ_{max} in the soil.

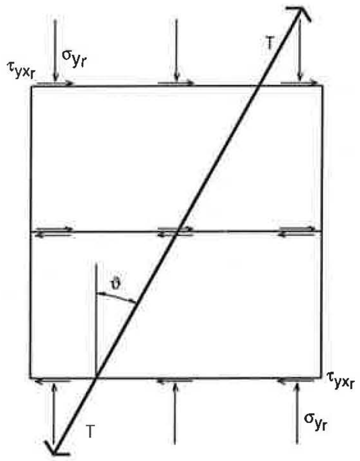

Fig. 2

Therefore:

$$\tau_{r\,max} = \sigma_r \cdot \tan\phi_{max} + (T/A_s) \cdot \cos\vartheta \cdot \tan\phi_{max} + + (T/A_s) \cdot \sin\vartheta \qquad (3)$$

where:

A_s = area of the soil element

$\tau_{r\,max}$ = maximum overall shear stress of the reinforced soil

Therefore the normal stress on the soil element is increased by:

$$\sigma = (T / A_S) \cdot \cos\vartheta \qquad (4)$$

while the maximum shear stress which the soil can carry is increased.

The main advantages of a reinforced soil structure are the following:

- lower global cost: the possibility to build steeper slopes reduces the quantity of fill material needed for an embankment;
- moreover, it is possible to use less valuable and then cheaper materials;
- improved stability: the reinforcement allows to increase the factor of safety;
- since a reinforced soil structure is inerhently flexible, it is possible to build directly on a foundation soil with low bearing capacity; a reinforcement at the base allows to build on soft soils, which would usually require a preliminary consolidation and great caution during construction.

4 MAIN APPLICATIONS OF GREEN FACED WALLS AND STEEP SLOPES

There are several typical applications for geosynthetic reinforced walls and steep slopes: the number and the kind of possible applications increase, as the technology develops and the soil reinforcement technique spreads all around the world. Here only few of the possible applications of green faced reinforced soil structures are illustrated.

4.1 *Landslides and slope failures*

Large and small landslides and failures of natural slopes (Fig. 3) often occur in areas where the value of the environment (for technical or economical or touristic or artistic reasons) call for the repair of the slope to the original (or as close as possible to the original) geometry.

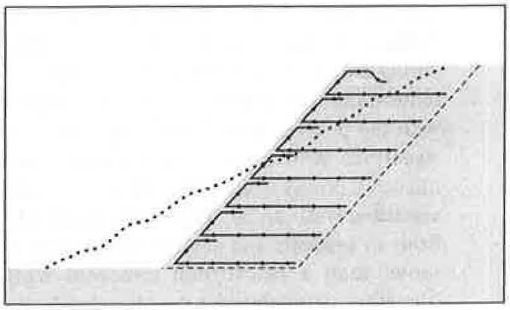

Fig. 3: Landslide repair

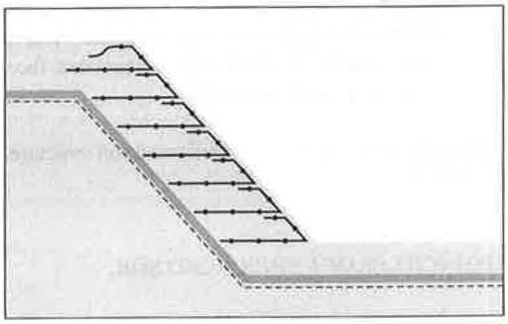

Fig. 4: Slope cutting repair

Geogrids or woven geotextiles allow to use the same soil of the landslide to reinstate the slopes, thus achieving large savings over the solution of importing a soil with better mechanical characteristics.

The geosynthetic reinforced slope can be easily vegetated with the local essences, in order to obtain the best integration with the surrounding environment.

4.2 *Slope cutting repair*

The installation of pipelines and other underground structures often requires to cut a slope in protected or valuable areas where the Authority imposes to repair the cutting to the original situation.

This may produce geotechnical problems due to the fact that the excavated soil results in lower mechanical characteristics than the original soil in the slope.

Geosynthetic reinforcement allows to improve the stability of the soil: the slope can be rebuilt without using expensive consolidation techniques (Fig. 4).

4.3 *Embankments and bunds*

There are many situations where the shortage of space or fill material calls for the construction of embankments and bunds with very steep slopes, greatly in excess of the naturally stable angle.
In all these cases geosynthetic reinforced soil structures provide a safe, sound and economical solution which can be used for some of these applications:

- noise protection bunds along highways, railways and airport taxiways (Fig. 5);
- blast protection embankments;

In these applications, the inherent flexibility, the ease of construction, and the use of any locally available fill soil are the technical and economical advantages of geosynthetic reinforced soil structures over other solutions.

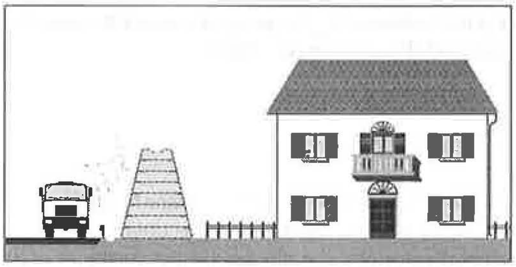

Fig. 5: Noise protection bund

4.4 *Shallow slopes reclamation*

Sometimes a shallow slope has to be converted to vertical or sub-vertical: as examples for enlargement of parking areas, land reclamation projects, housing developments, etc. (Fig. 6). Using geosynthetic reinforcement it is possible to build walls or steep slopes with almost any locally available fill soil, while the face can be built with a vegetated finishing.

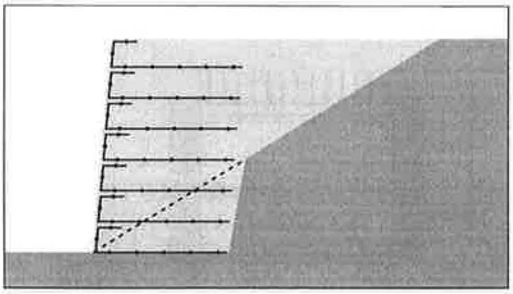

Fig. 6: Shallow slope reclamation

4.5 *Bridge abutments and wing walls*

For the construction of bridge abutments and wing walls (Fig. 7) the use of geosynthetics allows to solve the problems given by the high vertical and horizontal loads directly applied by the bridge deck, by dynamic loads from heavy traffic, by soft foundation soil, by high water table and environmental impact regulations.

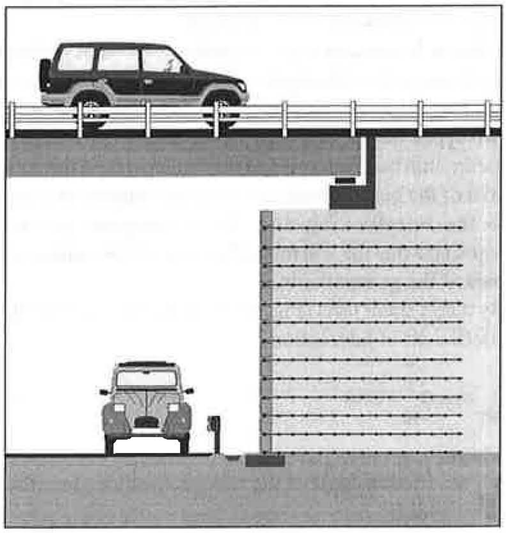

Fig.7: Bridge abutment

4.6 *Embankments*

Road and railways embankments (Fig. 8) require considerable quantities of fill soil and land take: the necessity to reduce the costs of fill soil and its transport from the quarries, as well as the value of the land and the loads to be carried by the embankment make geosynthetic reinforcement technically and economically advantageous when compared with traditional solution.

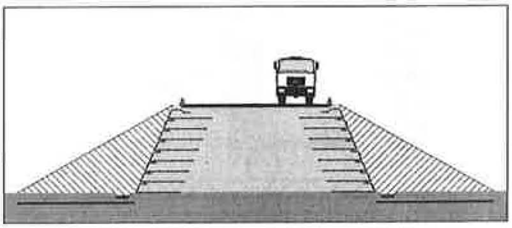

Fig. 8: Road embankment

5 PROPERTIES OF THE GEOSYNTHETICS USED FOR SOIL REINFORCEMENT

5.1 *Friction Behaviour*

The interaction between soil and geosynthetics used as reinforcement depends on the physical and mechanical characteristics of the soil, on the shape and stiffness of the reinforcements, and on the tensile stress at the soil-geosynthetics interface.

When a horizontal load is applied to a geosynthetic reinforcement with regular apertures, the resultant of the tangential stresses is due to the superposition of two types of stresses. The first component is due to the friction between soil and reinforcement on the solid area of the geosynthetic; the second component is due to the interlocking and the consequent passive resistance that the soil mobilises against the transversal bars of the geosynthetic.

By direct shear tests (Fig. 9) it is possible to define the coefficient of interaction

$$f_{ds} = \tan\phi_{sg} / \tan\phi \qquad (5)$$

where:

ϕ_{sg} = friction angle of the soil-geosynthetic interface [deg];

ϕ = friction angle of the soil [deg];

Typical values for the coefficient of interaction with geogrids (Picarelli et al, 1993) are

$$f_{ds} = 0.8 \div 1.0 \qquad (6)$$

The pull-out resistance of a geosynthetic is determined with pull-out tests: a geosynthetic is embedded within soil placed beneath and above it; a constant normal stress is applied while the geosynthetic is pulled horizontally at constant testing speed (Fig. 10).

The resistant shear stress to pull-out of the geosynthetic is given by:

$$\tau_b = \sigma_n f_{po} \tan\phi \qquad (7)$$

where:

f_{po} = factor of pull-out;

σ_n = normal stress [kPa];

The maximum pull-out resistant force that the reinforcement can develop is given by:

$$T_b = 2\,L\,B\,\tau_b \qquad (8)$$

where:

L, B = length and width of the reinforcement in the anchorage zone [m].

Typical values of f_{po} for geogrids ranges between 0.8 and 1.00 (Picarelli et Al., 1993).

5.2 *Tensile Strength*

A geosynthetic reinforcement is a plane bi-dimensional structure, with the thickness neglectible in respect to other dimensions: for this reason the tensile strength is defined for unit width of reinforcement.

As it concerns the geogrids, GRI-GG1 Test Method (GRI, 1987, a) suggests to perform tests on a single representative rib unit, and then to calculate the ultimate strength of the full structure in the direction of the test. The geogrid ultimate strength per unit width T_{grid} is given by:

$$T_{grid} = T_{rib} \cdot n_{rib} \qquad (9)$$

with:

n_{rib} = number of ribs in unit width [m^{-1}]

T_{rib} = tensile strength of a single rib [kN]

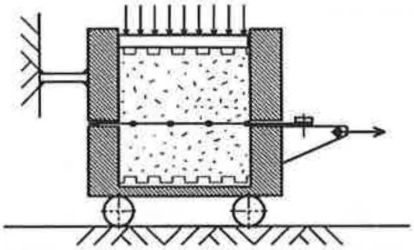

Fig. 9: cross section of geosynthetics direct shear apparatus

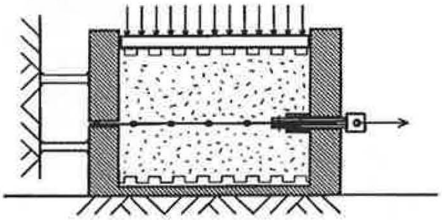

Fig. 10: cross section of geosynthetic pullout test apparatus

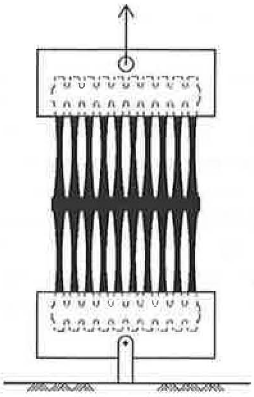

Fig. 11: wide width tensile strength test

The International Standard EN ISO 10319 for Wide Width Tensile Test, instead, requires that the specimen for geosynthetics is about 200 mm wide and shall contain at least one row of nodes, excluding the nodes held in the jaws (Fig. 11).

The Tensile Strength T is given by

$$T = T_{\text{Wide Width}} \cdot c \tag{10}$$

with:

$T_{\text{Wide Width}}$ = tensile strength of the specimen [kN];
N_m = number of tensile elements within 1 m width of the product [m^{-1}];
N_s = number of tensile elements within the test specimen [-];
b_s = width of the test sepcimen [m].
c = N_m/N_s for geogrids [m^{-1}];
c = $1/b_s$ for geotextiles [m^{-1}].

5.3 *Creep Behaviour*

Long term mechanical properties of the different available geosynthetics depend on the creep behaviour of the products. When a geosynthetic is subject to a given load, there will be a corresponding instantaneous deformation. If the deformation continues to increase without any increase in load or stress, it is said that the material is experiencing cold flow or creep. Creep can then be defined as increasing strain over time in the presence of constant stress and temperature. Creep is the result of the elastic-plastic-viscous response of a material under a sustained constant load. Creep of geosynthetics is known to depend on temperature, load, time, loading conditions, polymer and structure of the product.

Montanelli and Rimoldi (1993) show the creep behaviour of the PET woven geogrids in comparison to the HDPE extruded geogrids.
Through creep tests (Fig. 12) performed for at least 10.000 hours at different temperatures (typically 10°C, 20°C, 40°C), and using the time-temperature superposition principle (see Fig. 13) and suitable extrapolation techniques (Montanelli and Rimoldi, 1993), it is possible to determine the force T_{creep} which produces a maximum elongation of 10% under constant sustained load for 120 years.

HDPE geogrids show a creep behaviour depending on the characteristics of the polymer, while PET geogrids have a creep behaviour depending upon the structure of the product: the T_{creep}, for both of them, is about 40% of the tensile strength.

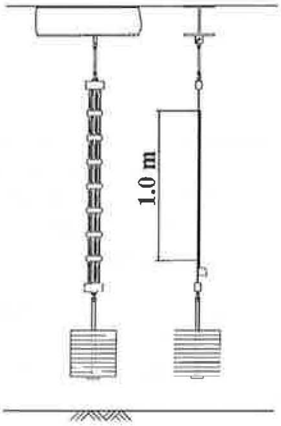

Fig. 12: creep tests

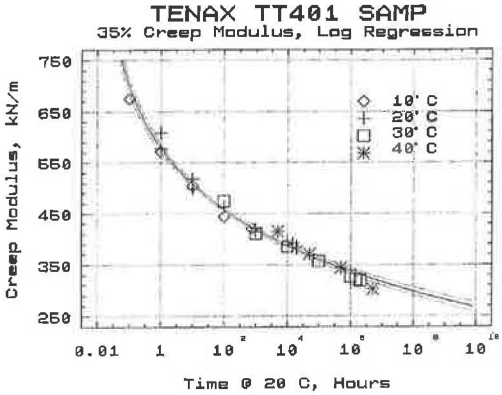

Fig. 13: Typical time-temperature shifting of the creep modulus of mono-oriented geogrids.

When T_{creep} has been determined in this way, the Long Term Design Strength (LTDS) is simply given by

$$LTDS = T_{creep} \qquad (11)$$

If it is not possible to carry out the creep test required to determine T_{creep}, the long term behaviour of a geosynthetic must be calculated from the short term tensile resistance, taking into account a Factor of Safety due to creep.
The LTDS in this case can be evaluated as

$$LTDS = T / FS_{creep} \qquad (12)$$

FS_{creep} is a function of the importance of the work, of the expected life and of the kind of reinforcement selected. For important projects the FS_{creep} ranges between 5.0 and 10.0.

5.4 *Junction Strength*

The strength of the junctions is a fundamental parameter for the evaluation of the lateral confinement provided by the geogrid and of its pull-out properties. Junction Strength can be evaluated using GRI-GG2 test, where the specimen is cut in the shape of a "T" (Fig. 14).
Since geogrids are designed on the basis of their LTDS, a rational approach to the specifications is that the junction strength F_j shall be at least equal to the LTDS multiplied by a proper Factor of Safety FS_j:

$$F_j > LTDS \cdot FS_j \qquad (13)$$

Montanelli and Rimoldi (1994) report on the junction strength of various types of geogrids.

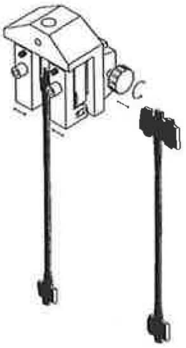

Fig. 14: Junction test specimen for geogrids

5.5 *Damage During Installation (DDI)*

Geosynthetic reinforcements can be damaged during installation and compaction of the fill soil because of the localized pressure and the abrasion applied by the coarse granules. It is then possible to have a reduction in the tensile strength of the reinforcement. Hence the LTDS of a geosynthetic shall be reduced by a proper Safety Factor. The value of this FS_{damage} can be found as the ratio of the original strength T of the geosynthetic to the strength $T_{exhumed}$ of the geosynthetic exhumed after installation:

$$FS_{damage} = T / T_{exhumed} \qquad (14)$$

Wright and Greenwood (1994) show the results of tests performed at TRRL following the procedure set by Watts and Brady (1990) for various types of geogrids

5.6 *Chemical And Biological Resistance*

To determine the Design Strength of a reinforcement to be used in a permanent application it is necessary to take into account the possibility that, during the life of the structure, the reinforcement could be subjected to a chemical or biological attack.
The proper Safety Factors $FS_{chemical}$ and $FS_{biological}$ can be determined by comparing the tensile strength of a reinforcement before and after exposure to a chemically or biologically aggressive environment.
The approved European Standard ENV 12225 for resistance to microbiological degradation (CEN, 1996) and the Draft Standards for resistance to hydrolisis (CEN, 1995, a) and for resistance to liquids (CEN, 1995, b), not yet approved, provide the procedures for these tests.

6 SOIL STRUCTURE

The design of geosynthetic reinforced soil walls and slopes has to consider all the possible failure scenarios and must ensure adequate Factors of Safety against each one of the failure conditions. Main distinction is made between internal and external failure modes, as illustrated in the followings.

6.1 *External Failure Modes*

To guarantee the external stability of a retaining structure a minimum Safety Factor against the

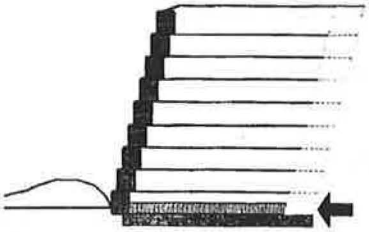

Fig. 15: Base sliding - the friction force at the bottom of the mass of reinforced soil is not sufficient to resist lateral earth pressures.

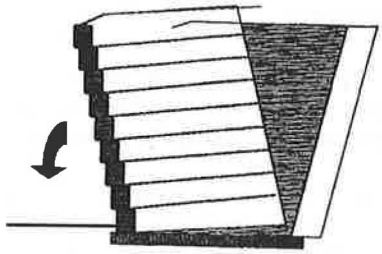

Fig. 16: Overturning - the base width of the reinforced mass is not wide enough to withstand the earth pressure and the upper part of the wall topples over the toe.

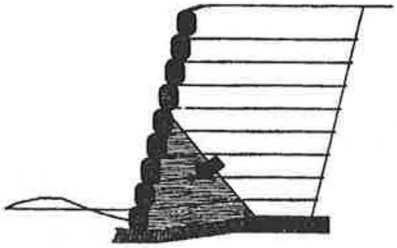

Fig. 17: Bearing capacity - The supporting subground is overloaded and is being pushed down and away.

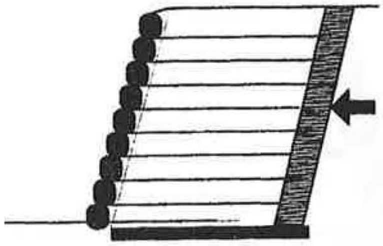

Fig. 18: Pullout - The reinforcing geosynthetics are not long enough, they slip out.

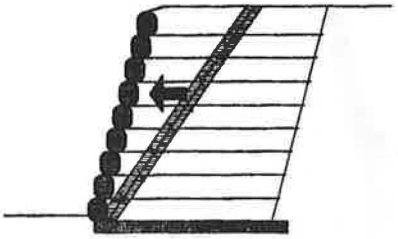

Fig. 19: Tensile overstresses - The reinforcing geosynthetics cannot withstand the tensile forces and rupture.

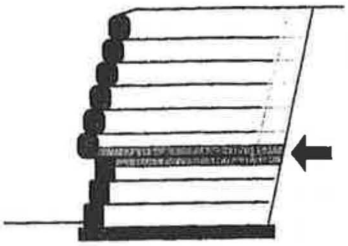

Fig. 20: Internal sliding - At a certain level friction is not sufficient and the upper part slides on the lower part of the wall.

following failure conditions must be guaranteed:

- base sliding (see Fig. 15)
- overturning (see Fig. 16)
- bearing capacity (see Fig. 17)

6.2. *Internal Failure Modes*

The resistance to internal failure mechanism of a reinforced soil structure has to be evaluated by establishing adequate safety margins for:

- pullout (see Fig. 18)
- tensile overstresses (see Fig. 19)
- internal sliding (see Fig. 20)

6.3 *Facing Failures*

Other causes of possible failures are local instabilities at transition zones between two different materials, that is:

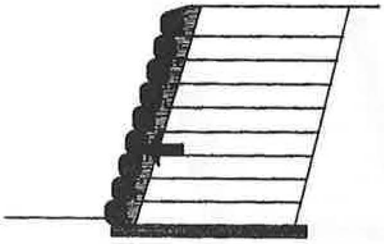

Fig. 21: Connection Failure - The connections of the reinforcing geosynthetics to the wall facing is not strong enough and they rupture or disconnect.

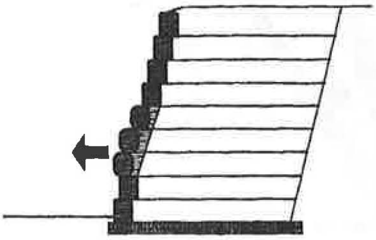

Fig. 22: Shear Failure (Bulging) - Parts of the wall are being pushed out due to local instability.

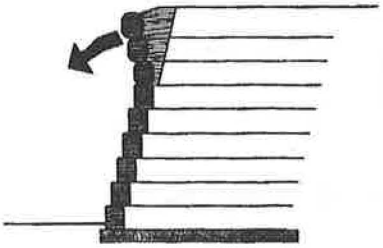

Fig. 23: Toppling - Some of the top facing units are being pushed over.

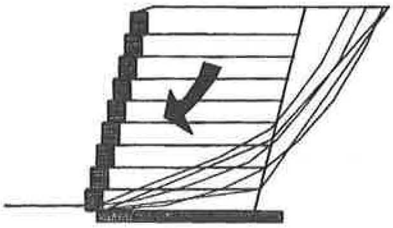

Fig. 24: Global Failure Mode - Example of failure surfaces (poligonal or circular) passing through the reinforced block and extending to the soil behind it.

- connection failure (see Fig. 21)
- shear failure (see Fig. 22)
- toppling (see Fig. 23)

6.4 *Global stability*

Failure surfaces passing through the reinforced soil block and extending beyond it or encompassing the foundation soil must be analyzed to ensure sufficient length and strength within the reinforced soil mass (see Fig. 24).

7 DESIGN CRITERIA

A slope with a greater angle than the limiting slope angle is a steep slope; to build a steep slope it is necessary to provide some additional forces to maintain equilibrium.

The reinforcing layers in the slope can resist the horizontal forces, thus increasing the allowable shear stresses. The forces that must be applied to the soil to maintain equilibrium can be added up in a gross force T that works in a horizontal direction, that is the direction of the reinforcements. Limiting now the analysis to internal stability, the gross force T may be expressed with the following equation:

$$T=1/2 \cdot K \cdot \gamma \cdot H^2 \qquad (15)$$

where:

H = height of the slope[m];

γ = unit weight of the soil [kN/m^3];

K = equivalent earth pressure coefficient, depending on the angle of the slope β, the soil strength parameters c and ϕ', and the pore pressure coefficient $r_u = u/(\gamma \cdot z)$.

For the case of vertical face, the coefficient K equals the coefficient of active earth pressure K_a; when β is between β_{lim} and 90°, K has a value between 0 and K_a. The additional forces required to provide equilibrium for a steep slope, with an adequate margin of safety in respect of any potential failure mechanism, can be determined by a limit equilibrium analysis. It consists in considering the possible failure surfaces in the soil and in comparing, for each of them, the active shear stresses and the resistant shear stresses in the soil. The Factor of Safety is calculated as the ratio of the maximum resistant shear force provided by the soil an

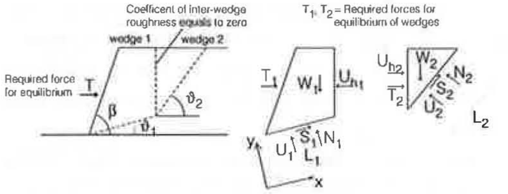

Fig. 25: Two part wedge method

instant before failure (that is in conditions of limit equilibrium) to the active force actually developed on the considered surface.

An extensive research allows to find out the surface that yields the minimum Factor of Safety, which must be compared with the one required for design needs. The possible failure mechanism may be the sliding along a plane surface, a circular surface (Leschinsky and Perry, 1988), a logarithmic spiral surface (Mangiavacchi et al., 1987) or a composed line, like two part wedge (Jewell, 1991).

7.1 *Two Part Wedge*

This method allows to determine the forces required for equilibrium, taking into account the geometry of the slope, the geotechnical properties of the soil, the pore water pressure and the surcharge loading.

The determination of the gross force required for equilibrium, by using the two-parts wedge mechanism, requires the following procedure (see Fig. 25):

set the node of the two blocks so that the angle ϑ_1 is set; systematically varying the angle ϑ_2 and imposing the equilibrium of forces, calculate the required force T_i, so that the maximum required force is obtained for every possible mechanism with the previously set node; repeat the calculation for a whole grid of nodes until the gross maximum required force T_{max} is found.

Once the type of reinforcement is defined, the aim of the design is then to provide sufficient reinforcing layers, distributed in such a way that in every point of each layer the available force is higher than the required force, with the pre-defined Safety Factor.

7.2 *Displacement Method*

The "displacement method" consider a geosynthetic reinforcement as a tensioned membrane. Mobilisation of tensile forces in the reinforcement depends on the displacement that is imposed on the slip line. The displacement of the active block correspond with the displacement at the top of the wall. A displacement field is imposed in the soil in the vicinity of the slip line. While the displacement of the block increase, the tensile force in the reinforcement and the inclination of the reinforcement itself along the slip line increase. For every vertical displacement of the top of the wall, the values of the angle and the tensile force are found (Fig. 26). The displacement is increased until a pair of values which stabilise the sliding block is obtained. The process is repeated for different slip surfaces. The critical slip surface is the one that yields maximum displacement in equilibrium conditions (Gourc et al., 1987).

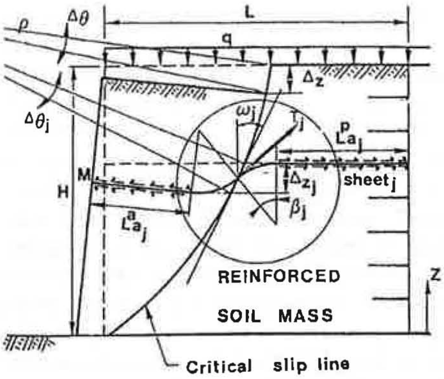

Fig. 26: Displacement method

8 DESIGN CODES AND DESIGN STRENGTH

At the moment, there are two official design codes that foresee the use of geosynthetic reinforcement with vegetated face: HA 68/94 and BS 8006.

8.1 *HA 68/94*

The HA68/94 "Design Methods for the Reinforcement of Highway Slopes and Soil Nailing Techniques" code, issued by the British Department of Transportation in 1994, adopts a limit equilibrium approach based on the two part wedge method. It has been chosen because it is conservative and easy in calculation (it is even possible to do simple hand checks). This code fully illustrates the use of the two part wedge method, providing the required equations for all the possible geometries of the slope, the water flow conditions, distributed loads and every kind of reinforcement, from geosynthetics to soil nailing. Design is based on limit state principles, incorporating partial factors. The slope is designed for both the ultimate (collapse) and the serviceability limit states (intended as the state in which movements of the slope or of the wall affect the function of the structure itself, or of the adjacent structures). The design life of the reinforced earthwork must be minimum 60 years. The limit equilibrium analysis is performed assuming that driving forces must be in equilibrium with resisting forces. Driving forces (soil weight and surcharge) are factored by a partial factor of unity. Resisting forces (shear strength of the soil and reinforcement force) are defined by mean of their design values, equal to the characteristic value divided by material partial factors of safety. No other factor of safety needs to be applied in addition.

8.2 *BS 8006*

The BS 8006 "Strengthened/reinforced soils and other fills" code, issued by the British Standard Institute in UK in 1995, deals with the design, construction and maintenance of reinforced soil structures, such as walls, abutments, slopes and foundations. The code provides also specific recommendations about the characterisation of the soils and about the factors of safety that should be used, and foresees all the type of load, including point loads, line loads, and distributed surcharges acting on the structure.

BS8006 is based on a limit state principle and considers (exactly like HA 68/94) two limit states: ultimate limit state and serviceability limit state.

Ultimate state is associated with collapse or structural failure of the earthwork, and is attained when disturbing design forces are equal or exceed resisting design forces. To provide an adequate factor of safety, partial material and load factors are used. Disturbing forces are increased by multiplying by load factors to have a design load, and restoring forces are reduced by dividing by material factors, to produce design strength. Serviceability limit states is attained when the deformation exceed prescribed limits. The prescribed numerical values of load factors are different from the ones used for the ultimate limit state. Only for the evaluation of the magnitude of differential or total settlements, all partial factors of safety (except those related to reinforcement) are assumed equal to 1.00.

The code uses four partial factors of safety: two load factors (applied to live and dead loads), a material factor and a fourth factor that take into account the economic ramifications of failure and reduces the design strength. As it concerns the reinforcements, resisting forces are determined on a statistical basis, hence BSI 8006 code can be defined as based on a probabilistic approach.

As it is not feasible to define unique values for the partial factors, prescribed ranges of these values are provided in the code.

As it concerns slopes with vegetated faces, the Code gives general guidance for external and internal stability analysis. The Code leaves the designer with the possibility to choose among a large number of methods to check internal stability: in particular, two part wedge, circular slip analysis, conjugate stress analysis, log-spiral analysis and coherent gravity method (for inextensible reinforcements) are suggested.

9 CONSTRUCTION SCHEMES

The construction methods for green faced reinforced soil walls and steep slopes can be summarized in 4 main schemes:

a) Straight reinforcement (Fig. 27a): mainly used for rather shallow slopes ($\beta<50°$), this scheme includes geosynthetics only for reinforcement, while the face is left exposed, or covered by a geomat or biomat. Therefore the reinforcing geosynthetics arrive just at the face, without any wrap-around.

b) Reinforcement wrapped around the face (Fig. 27b): in this scheme the same geosynthetic is used both for reinforcement of the fill and for face protection, by wrapping it around the face.

c) Mixed scheme: straight reinforcemene plus another geosynthetic wrapped around the face (Fig. 27c): in this scheme the two functions of reinforcement and face protection are played by two different geosynthetics. The reinforcing one has high tensile strength and modulus, while the one for face protection is lighter and is engineered to support the growing vegetation and to retain the soil, preventing wash out and erosion.

d) Front blocks tyed back by straight reinforcement (Fig. 27d): in this scheme a front block is used both to support the face during the construction and for providing the final face finishing. Blocks are usually made of compacted soil, encased in containers, made either of gabion baskets or of geosynthetics wrapped all around. Blocks are mechanically connected to straight reinforcing geosynthetics.

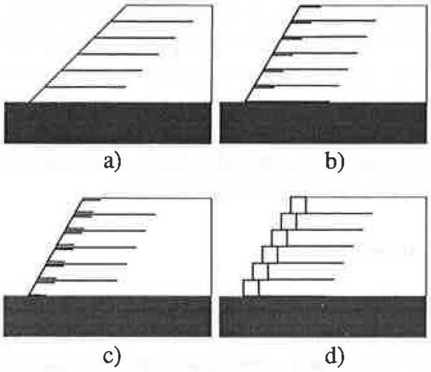

Fig. 27: The construction schemes for green faced structures: a) straight reinforcement; b) wrap-around reinforcement; c) mixed scheme; d) face blocks plus straight reinforcement.

10 CONSTRUCTION METHODS

10.1 *Straight reinforcement methods*

The construction methods based on the straight reinforcement scheme are the most simple, but they can be applied only with rather shallow slopes, when it is not necessary to provide an adequate face protection to the structure. The installation is very easy. The reinforcement is laid down horizontally and straight, then soil is spread and compacted to the required height, smoothing the face with a vibrating table or with the bucket of a back-hoe. Sometimes a protection (biomat or geomat) is used at the face to prevent erosion.

10.2 *Wrap Around methods*

The most widely used construction method in Europe has been, up to now, the "wrap around" technique, consisting in wrapping the geosynthetics around the face of the slope, in such a way to protect it from soil washing and progressive erosion.

The "wrap around" installation procedure can be used with or without formworks.

The use of formworks is particularly suggested when it is necessary to have a smooth and uniform face finishing.

The most simple construction method with the wrap around technique is without any formwork: it consists in placing a geogrid layer; in laying down, spreading and compacting the fill soil; in smoothing and levelling the face of the slope at the desired angle with a vibrating table or with the bucket of back-hoe; then the geogrid is wrapped around the face and fixed with a "U" staple. This method provides a fast construction and affords good results if it is not necessary to obtain a perfectly smoothed face. In fact, "bulging" of the face often occurs, with unpleasant aestethic effect.

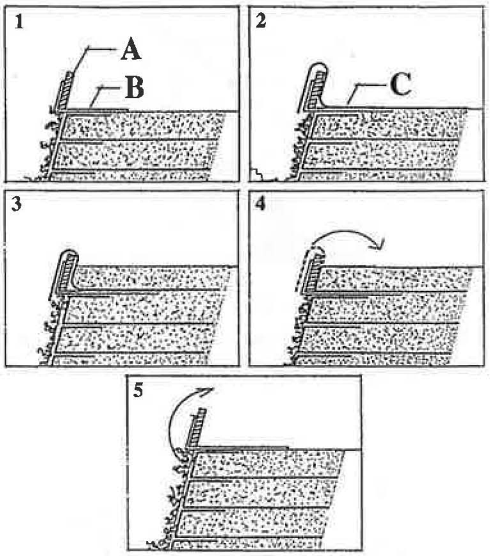

Fig. 28: Wrap around with movable formwork: A) timber board: B) scaffolding tube; C) geogrid.

Another method uses movable formworks; an example is given by scaffolding tubes with timber boards (Fig. 28): the formwork is placed near the edge of the slope, then a geogrid or geotextile is placed and anchored, leaving an edge outside the movable formwork. After laying down and compacting the fill soil, the geogrid is wrapped around the face and then the formwork is extracted (with a crane or a back-hoe) and used for the following reinforcement layer.

It is also possible to use a full size timber structure (Fig. 29) which will be removed only at the end of the work; timber boards are placed inside this structure and elevated as the slope increase.

Another method is to use steel bars (Fig. 30) to keep a timber board vertical during laying down and compaction of a soil layer: this technique usually allows to build only stepped slopes.

These wrap-around techniques provide a simple but

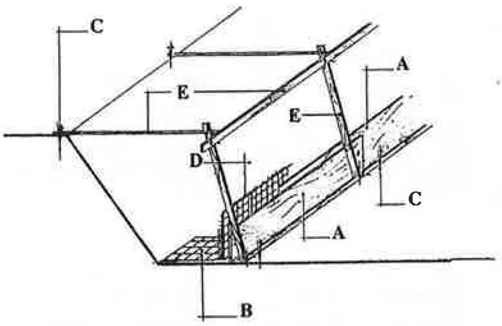

Fig. 29: Wrap around with a timber structure: A) timber board; B) geogrid; C) peg; D) turf; E) timber structure.

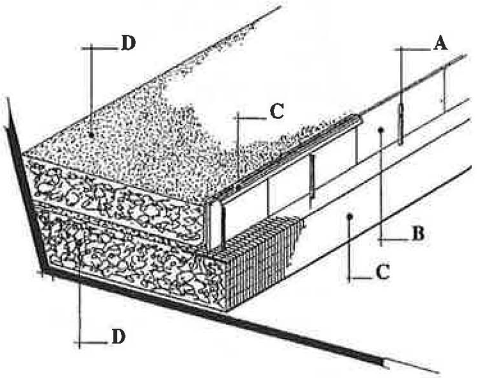

Fig. 30: Wrap around with timber tables and steel bars: A) steel bar; B) wooden board; C) geogrid; D) compacted soil.

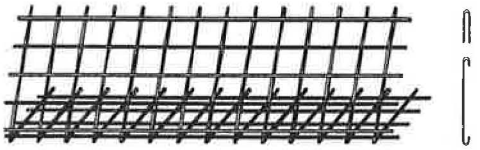

Fig. 31: The steel mesh formwork

relatively slow construction method. Moreover it requires a careful installation with good practice and experience to obtain a good face finishing, without bulging effects and with uniform grass cover.

The last development of the wrap-around methods consists in using a sacrificial steel mesh for supporting the face during construction (Fig. 31).

The steel meshes can be straight or shaped as a "L" or a "C". The steel meshes are left in place after the construction is terminated, which saves a lot of time and hence allows a very fast construction rate: a typical team of 4-5 workers well equipped and enough experienced, can install about 50m^2 of wall face in one working day, but in particular situations 100 m^2 of face in one day can be achieved. The reinforcing geosynthetic can be connected to the steel meshes but usually the two elements are independent.

10.3 *Mixed methods*

The mixed methods are characterised by the presence of a straight horizontal geosynthetic, and of another piece of reinforcement, sometimes different from the first, folded in "C" shape at the face. The straight geosynthetic act as a reinforcement, while the folded one prevent face erosion. The same formworks described for wrap-around methods can be used, including the sacrificial steel meshes.

10.4 *Front blocks methods*

These methods allow to build the face of the reinforced structure simply mounting one on top of the other pre-cast soil blocks, acting as a formwork for the fill soil. This method combines various technologies: the temporary steel forms, and the precise and efficient prefabrication including pre-seeding.

Prefabrication has the advantage of not being dependent on weather situations. The prefabrication does not disturb any traffic and can be near the site and covered against bad weather conditions. The prefabricated blocks can be shipped later by truck. A standard excavator is used to place the face blocks quickly and the same excavator is also used for backfilling. No hydroseeding is needed because the grass seeds are already included inside the face blocks and grass starts growing immediately.

Some local contractors produce the green blocks in advance and keep them at their yard ready for installation. The blocks are usually produced during periods of low workload, then stored away and sprinkled with water to have the grass growing even when on the stockpile.

11 PROPRIETARY SYSTEMS

Few proprietary systems, which use specifically geosynthetics as reinforcements, are patented in Europe in one or more Countries. Here is a short description of them.

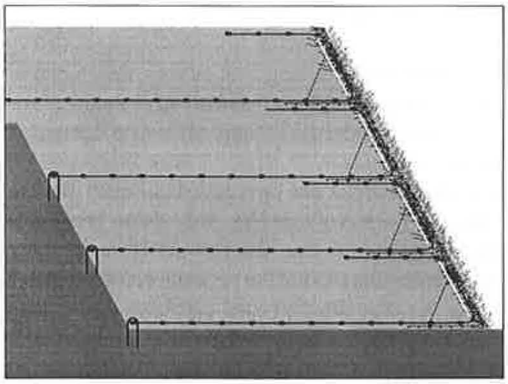

Fig. 32: The Tenax Rivel System

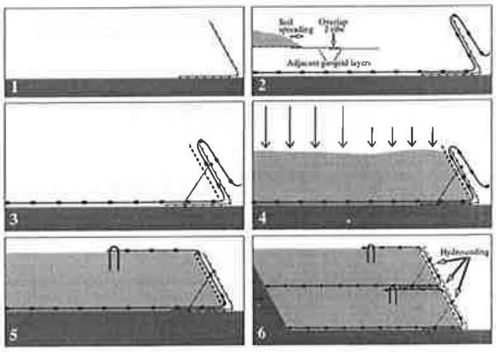

Fig. 33: Installation sequence for the TENAX Rivel System.

11.1 *RIVEL-TERRAMUR*

The RIVEL vegetated retaining wall system (Fig. 32), developed by Tenax SpA in Italy and known in Switzerland as Terramur system, represents a typical application of the "wrap-around" technique; it consists in the use of sacrificial steel mesh formworks that help in the construction of the steep slope and allow to obtain a highly uniform geometry of the face; moreover the time necessary for the construction and hence the costs of it are very low.

Rivel allows to create steep slopes with faces up to 70°-80°, completely vegetated thanks to the use of biomats, which provide a perfect medium for preventing the washout of the soil and for the support of the growing plants. The vegetation of the face is further enhanced by hydroseeding the face at the end of the construction of the reinforced soil structure.

To build a Rivel reinforced slope (see Fig. 33) it is necessary first of all to prepare the geogrids cut at the required length, and to bend the steel mesh sheets at the required angle. These sacrificial formworks are lined at the face of the slope, overlapped by about 50 mm and jointed by steel wires.

A biomat is placed on the internal face of the formworks; hooked bars are fixed to the formworks (one every 500 mm) connecting the horizontal and the inclined sides. The reinforcing geogrid is placed and anchored by means of U shaped staples. Soil is laid and spread on the geogrid in layers of about 300 mm; it is compacted by using a hand roller near the front of the slope (within 1 m), while the rest of the soil (more than 1 m away from the face) is compacted with a suitable roller compactor. Finally the geogrid is wrapped around the face, stretched and fixed with U shaped steel bars.

When the work is completed, the face is hydroseeded. It is also possible to place a jute net on the face of the slope to hide the synthetic elements and to protect the hydroseeding.

The Rivel system typically allows to build about 50 m² of wall face in one day, with typical team and equipment of 4 people, 1 truck, 1 excavator, 1 roller and 1 hand compactor.

11.2 *TEXTOMUR*

The TEXTOMUR system (Fig. 34), developed in Switzerland, uses a combination of steel mesh, nonwoven vegetation fabric and reinforcing nonwoven geotextile.

It is a typical example of a mixed construction scheme with sacrificial formworks. The vegetation fabric is laid inside the steel mesh, with the function of protecting the fill material against wind and water erosion and to support and carry the seeds, usually applied by hydroseeding. Finally, the needle punched polyester nonwoven fabric provides the reinforcement.

The Textomur system can be constructed with a minimum of 3-4 labourers (including machine operators), a back-hoe and a roller for compaction.

The construction sequence foresees the preparation of the base; the nonwoven reinforcing fabric is then unrolled; the retaining steel mesh is placed, with the vegetation fabric inside. Fill material is spread and compacted. The procedure is repeated for the other layers. The construction rate is similar to the Tenax Rivel one.

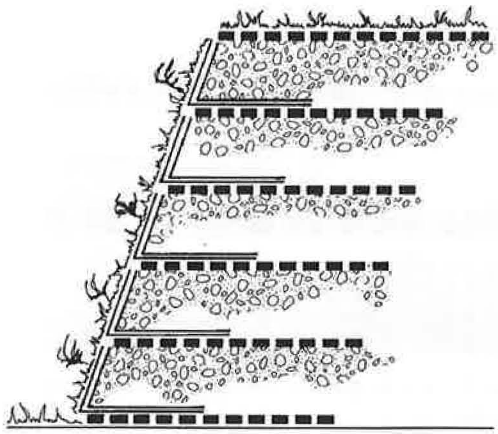

Fig. 34: The Textomur system

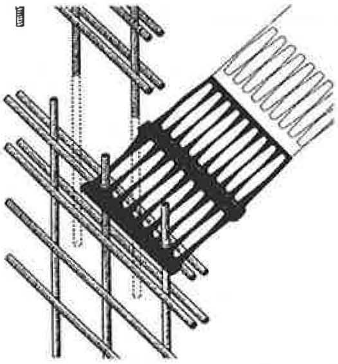

Fig. 35: The peculiar steel mesh formworks of the Mecamur system

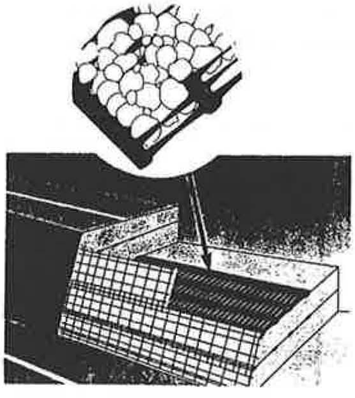

Fig. 36: The steel mesh panels of the Mecamur system are plugged into each other.

11.3 *MECAMUR*

MECAMUR is a retaining wall system, developed in Spain, characterised by a patented steel module (see Fig. 35) that provides the stability of the face, connected to HDPE geogrids.
These steel modules can be plugged into each other to obtain any geometry (see Fig. 36). As no geogrid is wrapped around the face, the stability in the long run is provided by the roots of the vegetation that is planted all over the face: the afterward corrosion of the steel, in this way, will not compromise the slope stability.
Anyway a geomat, and sometimes a biomat, is placed at the face to provide long term erosion protection and local stability. Therefore MECAMUR adopts a mixed construction scheme, with plane sacrificial formworks, which doesn't require bending operations.
The method is characterised by the peculiar steel modules, which allow a very flexible construction: as an example, to achieve a changing geometry, for instance a given slope changing to another, it is only necessary to adapt the steel modules without the need of any special piece.
The construction rate is slightly faster than with Rivel or Textomur, thanks to the straight plane formworks.

11.4 *TERRAMESH*

The Terramesh system, developed by Maccaferri SpA in Italy, is a Geosynthetics Associated Technology, since it is a reinforced soil system for retaining walls that uses wire meshes as reinforcement. Two different solutions are possible; the first one foresees a face made of gabions (usually 1.00 m thick) filled with coarse gravel or topsoil, connected to layers of double twisted wire mesh. The wire meshes are provided already cut to the required length and they are sandwiched between layers of compacted selected fill (Fig. 37).

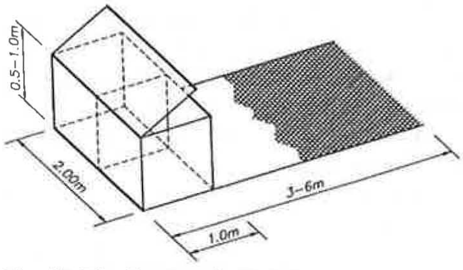

Fig. 37: The Terramesh system

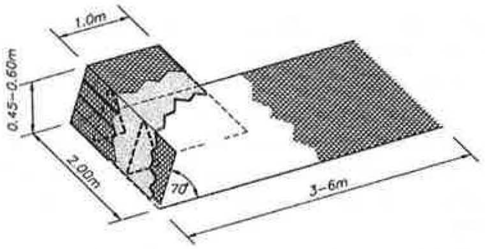

Fig. 38: The Terramesh green system

Terramesh Green has the external face consisting of vegetative soil; the construction scheme foresee laying down a double twisted wire mesh, wrapped around the face, with a biomat (or a polypropylene geomat in case of application with water) at the face; the wire mesh on the face is kept in position by means of triangular steel brackets (Fig. 38).

11.5 *TERRA BLOC*

Terra Bloc is a system for geogrid reinforced slopes with pre-cast soil blocks at the face (Fig. 39), developed by Sytec Bausysteme in Switzerland.
The face element is a triangular prism with one of the faces vegetated by pre-cut turf pieces. The base and the triangular lateral sides of the prism are closed with a steel mesh, while a geotextile is folded all around the block, with the exclusion of the face side. A bi-directional PP geogrid is wrapped around the prism: the geogrid creates also a loop used for moving and placing the blocks. The depth of the block is 600 mm, the height is about 500 mm and the length of it ranges between 2 and 4 m.
The base of the slope to be reinforced must be well compacted; the soil block are lifted with a crane or an excavator through the loop and placed. After placing, the loop is folded toward the outside of the slope to be built, over the vegetated face of the block. Then about 250 mm of soil are laid down and compacted. The loop is now opened and the geogrid (for a maximum length of about 2.5 m) is placed over the compacted soil. Then other 250 mm of soil are laid and compacted.
The upper surface of the compacted soil becomes the new base for another reinforced layer (Fig. 40). If longer geogrid length are required, straight layers are connected to the bidirectional geogrid of the face blocks.
Terra Bloc gives the possibility to have a face vegetated a few days after the end of construction, or even immediately after construction.

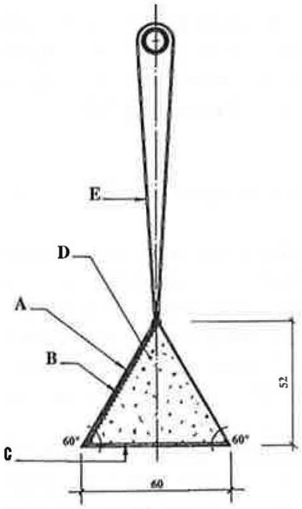

Fig. 39: The Terra Bloc system face block: A) biaxial geogrid; B) turf; C) steel mesh; D) soil; E) loop.

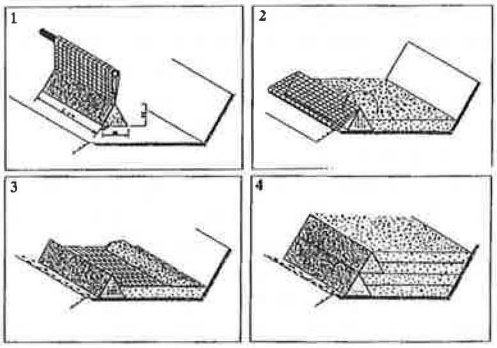

Fig. 40: The construction procedure for the Terra bloc system

11.6 GEOGREEN

The Geogreen system, developed by Dr. Felix Jaecklin in Switzerland, is another example of the face block construction scheme.
In this system gabions are filled with local soil. This method allows to prefabricate series of gabions in a convenient area, away from congested traffic, using local borrow fill material and seeds.
The green gabions are made by using a steel cage, filled face down for precise seeding and a better topsoil spreading. The filling is easy and convenient and it achieves a uniform compaction, which ends up in a

neat facing. The completed gabions are mounted one on top of the other and then backfilled. Both geogrids and geotextiles can be used as reinforcement. A typical Geogreen retaining wall is shown in Fig. 41.

12 DESIGN UNIFICATION AND FUTURE NEEDS

Today it is standard practice to use partial safety factors for the design of geotextiles or geogrid reinforced retaining structures. The philosophies being applied vary considerably from country to country and therefore a design may be acceptable in one place but somewhere else not because of widely differing opinions and variations of partial safety factors.

The coordination of engineering practice and world wide experiences would be of great help to the design engineers and to the future unification of national codes and specification requirement.

It doesn't need a summary of various recommendations in different design manuals to demonstrate the need for such thorough study and research. Moreover, it is well understood that the safety factors influence the design of any reinforced soil structure considerably and thus they are of great economical importance. It can be concluded that there is a wide range od diverging opinions on a scarcely known subject. The designers must be particularly prudent in the use of non chemically stabilized Polyesther geosynthetics under high pH-values and of non oriented Polypropylene geosynthetics under very high permanent loads for creep and for fatigue reasons. These considerations are very general and they are to be analized for each project, depending on type of geotextile or geogrid used and the actual project application.

A few years ago the standard design methods for reinforced walls were performed with hand calculation. However in the last ten years various computer programs have been developed to run design calcualtions quickly and with confidence. Today manual design calculations are for preliminary design checks only.

The available design softwares can be summarized under the following categories:

- two part wedge, displacements method or circular arc failure type methods with horizontal forces to simulate the effect of reinforcing layers;
- design program for anchored deep excavations;
- design programs for soil nailing or rock nailing.

Usually, these programs do not fully cover the behaviour of reinforced soil structures with regards to all the failure mechanism mentioned at Paragraph 6.

Anyway, the authors collected several design softwares for reinforced walls with the purpose to extend experience and confidence into such computer programs and possibly derive some conclusions on general trends of the results. Most of these programs were developed by the manufacturers with the aim of helping to spread confidence in the safe use of the products.

The programs were used to design the very same sample walls (see Fig. 42) and then to compare tensions, safety factors and ultimately material use and cost. The extensive work carried out showed that each program applies a different safety factor philosophy, different failure planes and failure modes (some use block sliding, other use circular arcs, some even combined failure plains).

The results of the calculations with 6 different softwares are listed in Table 1, which shows clearly that the differences in design methods and safety factors finally bring to very wide differences in the total amount of reinforcement required.

We can also point out the followings about design softwares:

- Computer programs often result in a much higher amount of reinforcement used, because the hand calculation checks only one or only a few failure planes, whereas the computer program searches automatically for many failure planes to find the most critical one. This explains the frequent discrepancy between computer and hand calculation.
- The older programs and the less sophisticated programs sometimes end up with less total reinforcement quantity. This does not mean more is always better, yet it means less may simply be unsafe.
- Different geosynthetics length and quantity are due also to the different behaviour of the reinforcement

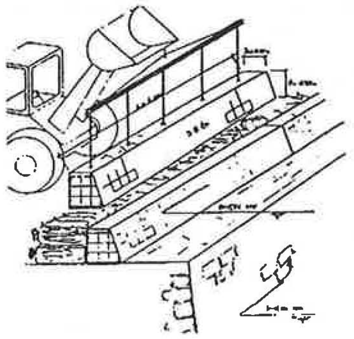

Fig. 41: Installation of the face blocks of the Geogreen system

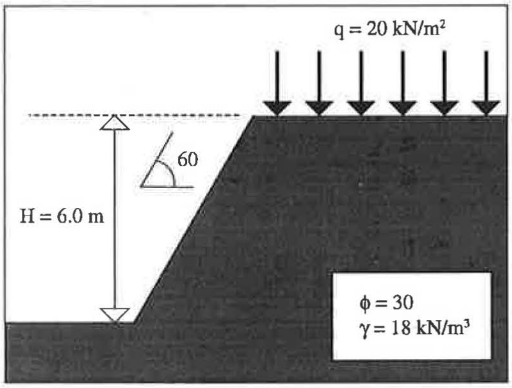

Fig. 42: Design exercise

Tab. 1 - Comparison of results of design exercise with different softwares

N.	Software	LTDS (KN/m)	L (m)	n	Lxn (m)	LtotxLTDS (m)	Rank (%)
1	Leshinsky	29.5	6.5	10	65.0		
		20.7	6.0	10	60.0	3160	154
2	NCMA	21.5	5.3	9	47.3		
		16.5	5.3	12	63.0	2055	100
3	Huesker 95	28.2	6.0	7	42.0		
		11.1	6.0	12	72.0	1984	97
4	Mirafi	35.0	5.8	9	25.2		
		25.0	5.8	10	58.0	3277	159
5	Polyfelt	10.5	8.0	33	264	2772	135
6	Tensar	19.5	5.0	4	20.0		
		11.8	5.0	16	80.0	1334	65

LTDS	Long Term Design Strength
L	length of geogrid
n	number of geogrid layers
Lxn	total length of geogrid
LtotxLTDS	parameter for comparison
Rank	percentage away from NCMA reference

used. As shown in the previous chapters, the friction behaviour, the junction strength, the resistance to damage and to chemical and biological attacks highly influence the partial Factors of Safety used in the calculations.

- Many computer programs have internal limitations. The NCMA e.g. operates for walls up to 15 m only, which is a safe limit anyway; even though much higher walls can be built, yet very professional approach is needed.
- Many programs do not accomodate for slanted wall faces.

The comments and conclusions are far from final. They are mentioned here to raise some flags for better attention, yet they are not meant to disqualify or criticize. A much larger number of test runs would be needed for final evaluation.

13 CONCLUSIONS

The present evolution of green faced reinforced soil retaining structures has come to a high degree of sophistication and differentiations, both in construction techniques and design method.

A great effort for harmonizing and standardizing the huge amount of knowledge about geosynthetics testing, construction methods and stability analyses need to be made by the geosynthetics community for making reinforced soil popular to a larger public.

ACKNOWLEDGEMENTS

The Authors wish to thank Mr. Piergiorgio Recalcati, Miss Mara Giani and Mrs Dolores Brambilla for their invaluable contribution in the preparation of this paper.

REFERENCES

BSI (1995) *"BS 8006: Code of practice for Strengthened/reinforced soils and other fills"*.

CEN (1986) "ENV 12225 - Geotextile and Geotextile Related Products - *"Resistance to microbiological degradation"*, CEN, Bruxelles, Belgium.

CEN (1995, a), "ENV 00189031- Geotextile and Geotextile Related Products - *"Screening test method for determining the resistance to hydrolisis"*, Draft July 1995, CEN, Bruxelles, Belgium.

CEN (1995, b), ENV 00189029 - Geotextiles and Geotextile Related Products- *"Screening test method for determining the resistance to liquids"*, CEN, Bruxelles, Belgium.

Giroud, J.P. (1986) *"From geotextiles to geosynthetics: a revolution in geotechnical engineering"* Opening Lecture, Proc. 3rd Int. Conf. on Geotextiles, Vienna, Austria.

Gourc, J.P., Ratel, A., Gotteland, Ph. (1987), *"Design of Reinforced Soil Retaining Walls: Analysis and Comparison of Existing Desing Methods and Proposal for a New Approach"*, Proceedings of the NATO Advanced Research Workshop on Application of Polymeric Reinforcement in Soil Retaining Structures, Kingston, Ontario, Canada.

GRI (1987, a) "GRI-GG1 "*Standard Test Method for Geogrid Rib Tensile Strength*" Geosynthetics Research Inst., Philadelphia, USA.

GRI (1987, b) "GRI-GG2 "*Standard Test Method for Geogrid Junction Strength*", Geosynthetics Research Inst., Philadelphia, USA.

Jewell, R.A. (1991), *"Application of revised design charts for steep reinforced slopes"*, Geotextiles and Geomembranes, Vol. 10, No. 3, 1991, pag. 203 - 234.

Jones, C.J.F.P. (1985), "*Earth reinforcement and soil structures*" Butterworth Publ., London, UK.

Leshchinsky, D. and Perry, E.B. (1988) *"On the Design of Geosynthetics Reinforced Walls"*, Geotextile and Geomembranes, Vol. 8 No. 4, Elsevier Applied Science, UK.

Mangiavacchi, R., Nova, R. and Pellegrini, G., (1987), *"Analisi di stabilità dei muri in terra rinforzata"*, ("Stability analysis of reinforced soil walls"), Rivista Italiana di Geotecnica, Anno XX, n.3 (in Italian, with English abstract).

Montanelli, F. and Rimoldi, P. (1993) *"Creep and Accelerated Creep Testing for Geogrids"*, Proceedings of Geosynthetics '93 Conference. Vancouver, Canada.

Montanelli, F. and Rimoldi, P. (1994) *"The Development of Junction Strength Test for Geosynthetics"*, Proceedings of the 5th International Conference on Geotextiles, Geomembranes and Related Products. Singapore.

Picarelli, L., Cazzuffi, D., Ricciuti, A. and Rimoldi, P. (1993), *"Laboratory investigations on the shear strength of geogrid reinforced soils"*, Proc. ASTM Symp. on Geosynthetics Soil Reinforcement Testing Procedures. San Antonio, USA.

Rimoldi, P., Cazzuffi, D., Moraci, N., Ionescu, A, (1995) *"Geosynthetics, please - not geoconfusion!"*, IGS News Vol. 9 N. 1, March 1993.

Schlosser, F., Jacobsen, H. M., and Juran, I. (1983), *"Soil reinforcement"*, General report, Proc. 8th Eur. Conf. Soil Mech. Fndn. Engng., Vol 3, Helsinki.

Watts, G.R.A. and Brady, K.C. (1990) *"Site damage trials on geotextiles"*, Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products. The Hague, The Netherlands.

Wright, W.C.A. and Greenwood, J.H. (1994), *"Interlaboratory trials on installation damage in geotextiles and comparison with site trials"*. ERA Technology, Report 93-0915, Surrey, England.