# Design Method for Cover Soil Stability of Lined Multi-slope/berm Systems using Continuous Geogrid Reinforcement

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**ABSTRACT**
**To keep in stable conditions cover soil layers laid on smooth lined slopes is a frequent problem in landfill cappings and basins. For single slopes, one way to obtain a stable system is to place a geogrid along the slope, which can hold driving forces and transmit them in an properly dimensioned anchor trench, located at the crest of the slope. In this paper a new design method is proposed for complex systems constituted by "n" slopes and "n-1" berms making use, if convenient, of only one geogrid. The development of tensile forces in the geogrid, along the slope profile and in the anchor trench, is taken into account. At the same time, the problem of the cover soil uplift in critical concave corners is also considered. Finally, some considerations about the performance characteristics that a reinforcement geogrid should fulfill, are made.**

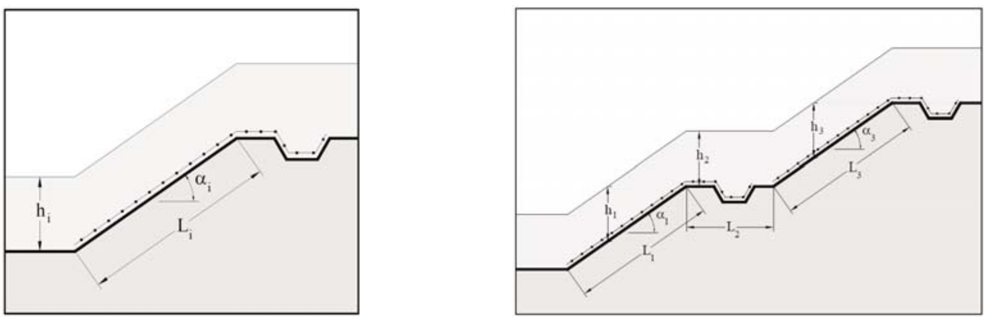
**RESUMEN**
**Un problema frecuente en las cubiertas de rellenos sanitarios y en los lagos impermeabilizados con geomembranas es mantener en condición estable el terreno de cobertura dispuesto sobre los taludes lisos. En el caso de taludes simples, un modo de obtener la estabilidad consiste en disponer sobre el talud una geomalla que sea en grado de absorver las fuerzas de deslizamiento y de transmitirlas a una trinchera de anclaje, oportunamente dimensionada, dispuesta en la cresta del mismo. En este artículo se propone un nuevo método de cálculo para sistemas complejos constituídos por "n" taludes y "n-1" bermas empleando, si resulta conveniente, solo una geomalla. El método permite obtener los cambios de tensiones en la geomalla a lo largo del perfil del talud y en la trinchera de anclaje. También se analiza el problema del levantamiento del suelo de cobertura en correspondencia de los vértices cóncavos.**

## 1. INTRODUCTION

**To achieve the impermeability on landfills cappings and basins is common the use of geomembranes that are, afterwards, usually covered with soil layers. Along these inclined surfaces is difficult to keep soil layers in stable condition, due to the low shear strength values between the interface soil/geomembrane. Often, even with sweet slopes angles, driving forces exceed holding forces and tends to move the soil downwards. One way to reach the stability is to place a suitable geogrid along the slope able to hold the over driving forces and to transmit them in a proper dimensioned anchor trench, located at the crest of the slope.**

**Nowadays, several design methods take in consideration only a single slope, therefore, in case of multi slopes separated by berms , the problem is commonly solved dividing the whole slope in many single ones (Fig. 1). This assumption leads to interrupt the reinforcement continuity at every berm generating, from a practical point of view, two problems: difficulties of installation and necessity to realize many anchorage trenches, that is not always possible.**

**On the other hand, the tensile forces taken by the geogrid are transferred directly to the anchor trench, without considering the several changes of direction of the geogrid in every corner, including the trench. This assumption leads to over dimensioning the anchor trenches, resulting that the minimum required size of the anchor trench, is often not practicable. From a practical point of view, is difficult to realize big trenches on berms and, if possible, contractors prefer to laid at once only one type of geogrid along the total slope section.**



**a)** **b)**

**Figure 1. a) single slope system. b) multislope system divided in many single slopes.**

**In this paper a new design method is proposed to determine the required tensile strength of the reinforcement and the size of the anchor trench at the crest for complex systems constituted by "n" slopes and "n-1" berms with any inclination angles and lengths. The shape of the total system is taken into account so the mathematical model can be considered closer to the "actual" structural configuration. The development of tensile forces in the geogrid, along the slope profile and in the anchor trench, is determinate, considering the variation of tensile forces due to the help of friction and change of direction. This approach allows a reduction of the anchor trench dimensions compared with "usual" methods.**

**In case of continuous reinforcements, an additional issue has to be taken into account: is the potential uplift of the cover soil in particular critical points, that is, not only in correspondence of the anchor trench but along the berms as well. The cover soil can be uplifted due to the tensile strain of the geogrid in correspondence of concave corners, with the consequent risk of overall sliding. This complex phenomenon is analyzed in an unsophisticated way using the principle of cables.**

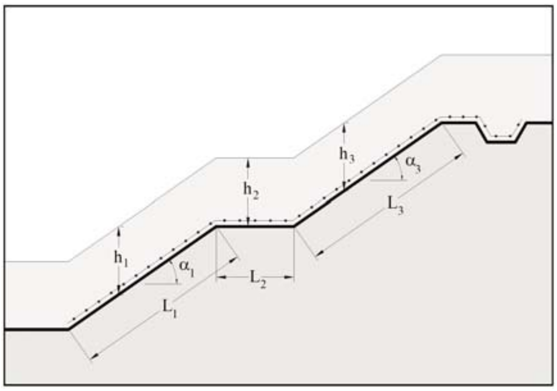



**Figure 2. Multislope system using one geogrid.**

**In the following chapters first, four local situations commonly present in this kind of systems will be analyzed, followed by the description of the procedure for the design of multislopes systems combining this four cases. At first the problem is analyzed from the ultimate state approach, taking into account factors of safety (according with Eurocode 7), in order to evaluate the required tensile strength for the geogrid; then the system is analyzed from the serviceability point of view in order to evaluate the deformations, with particular regard to the uplift problem.**

**Finally, some considerations about the performance characteristics that a reinforcement geogrid should fulfill, are made.**

## 2. ANALYSIS OF SINGULAR CASES

**The characteristic shape of the multisolpes systems, made by a sequence of slopes and intermediates berms with a final anchor trench at the top, leads to individuate four typical cases that must be taken in consideration.**

**These four different situations are developed separately below, that is: 1) Analysis of rectilinear slopes, 2) Transmission of the geogrid tensile strength through convex corners), 3) Transmission of the geogrid tensile strength through concave corners and uplift checking, 4) Checking of the "tooth of soil" between the anchor trench and the slope against shear failure.**

### 2.1 Analysis of rectilinear slopes

**The calculation of the tensile strength developed in the geogrid along rectilinear slopes is performed simply applying the equilibrium equations on the system represented in figure 3 . Is assumed that $\tan\phi_{soil} > 1.1 \times \tan\alpha$**

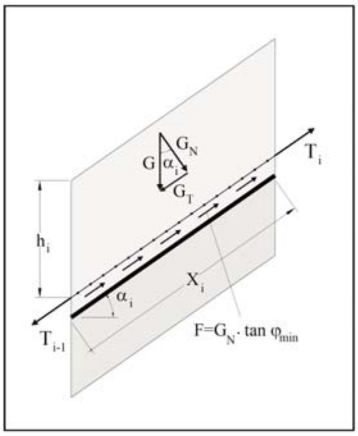



**Figure 3. System of forces in rectilinear slopes.**

$$G = \gamma \cdot h \cdot x \qquad [1]$$

$$G_N = \gamma \cdot h \cdot x \cdot \cos\alpha \qquad [2]$$

$$G_T = \gamma \cdot h \cdot x \cdot \mathrm{sen}\alpha \qquad [3]$$

$$F = G_N \cdot \tan\varphi_{min} = \gamma \cdot h \cdot x \cdot \cos\alpha \cdot \tan\varphi_{min} \qquad [4]$$

$$\sum F_T = 0$$

$$T_{i-1} + G_T - F - T_i = 0 \qquad [5]$$

$$T_i = \gamma \cdot h \cdot x \cdot (\mathrm{sen}\alpha - \cos\alpha \cdot \tan\varphi_{min}) + T_{i-1} \qquad [6]$$

**Where:**

**G = total weight of the soil in the considered stretch [kN/m]**

**$G_T$ = tangential component of G with regards to the slope [kN/m]**

**$G_N$ = normal component of G with regards to the slope [kN/m]**

**$\gamma$ = unit weight of soil [kN/m$^3$]**

**h = cover soil thickness [m]**

**x = variable along the slope ($0 \leq x \leq L$=slope length) [m]**

**$\varphi_{min}$ = minimum friction angle along the most critical interface layer [°]**

**F = friction resistance [kN/m]**

**T = tensile strength in the geogrid [kN/m].**

**The total weight of soil G is decomposed into two components: $G_T$ tangential and $G_N$ perpendicular to the slope. Generally the tangential components $G_T$ generates driving forces, unless the considered single slope is in counter inclination with regards of the main slopes that defines the overall sliding sense (this particular situation can take place in case of berms with small counter inclination and in the anchor trench). The normal component $G_N$ helps the stability mobilizing the friction resistance through the minimum friction angle $\varphi_{min}$. In case of multilayers systems, that is, barriers made with several types of geosynthetics (GCLs, geomembranes,**

drainage geocomposites, etc) the friction angle $\varphi_{min}$ to take in consideration is the minimum between the several interface layers. When the inclination of the slope $\alpha$ is higher than $\varphi_{min}$, driving forces exceeds holding forces, and the group of materials that are above the critical interface layer tends to slide down. The geogrid has the function of equilibrating the deficiency of holding forces, therefore it must be able to resist at the working stresses along the design life with a reliable factor of safety.

Seismic loadings and its combinations (vertical, horizontal) can be applied on the soil mass G. The loading due to the presence of water, in hydrostatic condition, can be considered in similar way than the weight of soil. Hydrodynamic flows are over the purpose of this paper and should be analyzed separately. In any case, is strongly recommended to foresee a drainage layer between the cover soil and the liner, perhaps placing a drainage geocomposite under the geogrid or placing a layer of gravel on the reinforcement. Additional loadings during installation due to mechanic means (i.e. bulldozers, excavators, tracking means) can be transformed into static loads, applying a suitable incremental factor for the dynamic action .

In this design procedure is not considered the collaboration of the passive earth pressure at the toe of the slope. Frequently the thickness of cover soil is very small compare with the slope length, thus the influence of the passive earth pressure in the cover soil stability, is negligible. Certainly, the omission of the passive pressure helps to be in the safe side. In any case, if considered relevant, the passive pressure can be calculated applying well known methods. When the toe is strong the sliding problem is transferred just above itself.

### 2.2 Transmission of the geogrid tensile strength through convex corners

To calculate the variation of the strength in the geogrid after a change of direction along a convex corner is possible to use the mathematical model represented in figure 4.

In this circumstances, when the geogrid is pulled down due to driving forces, has a certain tension $T_{i-1}$ before the corner. As soon as the geogrid change direction around the corner, performs a pressure along its concave side pressing the geomembrane. Due to the friction between the geogrid and the liner and the curvature angle of the corner, the strength decreases progressively until the geogrid leaves the corner.

In figure 4 is considered an infinitesimal segment arc of geogrid between two points ($x_{i-1}$, $y_{i-1}$) and ($x_i = x_{i-1}+ dx$ , $y_i = y_{i-1} + dy$), in which are applied the tangential forces $T_{i-1}$ and $T_i$, with tangent angles of $\alpha_{i-1}$ and $\alpha_i$ respectively, as regards as to the horizontal. The friction resistance between the geogrid and the contact surface is dF, that is a function of the normal force dN and the friction angle $\varphi_{min}$ .

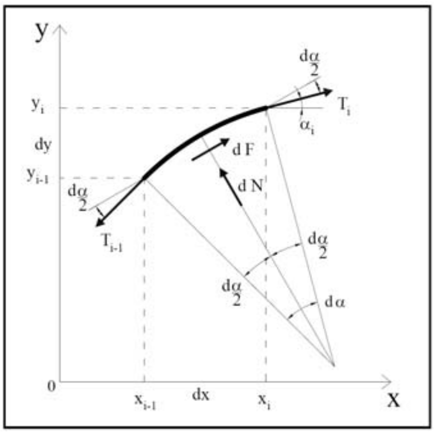



Figure 4. Scheme of forces in convex corners.

$$T_{i-1} = T_i + dT \quad [7]$$

$$\alpha_i = \alpha_{i-1} + d\alpha \quad [8]$$

The relative angle between $T_{i-1}$ and $T_i$ is

$$d\alpha = \alpha_i - \alpha_{i-1} \quad [9]$$

The relation between the friction and the normal pressure is:

$$dF = dN \cdot \tan \varphi_{min} \quad [10]$$

**where $\varphi_{min}$ is the minimum value of friction angle in static condition between surfaces in contact under the geogrid.**

**The system of forces on the plane must be in equilibrium, so applying the equilibrium equations parallel to the surface direction:**

$$\sum F_{=} = 0 \quad \Rightarrow \quad T_{i-1} \cdot \cos(d\alpha/2) - T_i \cdot \cos(d\alpha/2) - dF = 0 \quad [11]$$

**Because $d\alpha$ is an infinitesimal angle is possible to consider $\cos(d\alpha/2) \approx 1$, $\text{sen}(d\alpha/2) \approx d\alpha/2$, so:**

$$dT = dF \quad [12]$$

**Therefore, the reduction of tension T is equal to the increment of friction along the considered segment of arc.**

**Summation in the perpendicular direction:**

$$\sum F_{\perp} = 0 \quad \Rightarrow \quad dN - T_{i-1} \cdot \text{sen}(d\alpha/2) - T_i \cdot \text{sen}(d\alpha/2) = dN - T_{i-1} \cdot \frac{d\alpha}{2} - (T_{i-1} + dT) \cdot \frac{d\alpha}{2} = 0$$

**[13]**

**Neglecting the 2nd order quantities:**

$$dN = T_{i-1} \cdot d\alpha \quad [14]$$

**Considering the equations [10] and [12]:**

$$\frac{dT}{T} = \tan \varphi_{min} \cdot d\alpha \quad [15]$$

**integrating:**

$$\int_{i-1}^{i} \frac{dT}{T} = \tan \varphi_{min} \cdot \int_{i-1}^{i} d\alpha \quad [16]$$

$$T_i = \frac{T_{i-1}}{e^{\tan \varphi_{min} \cdot \Delta\alpha}} \quad [17]$$

**With $\Delta\alpha$ = relative angle between the forces $T_i$ and $T_{i-1}$**

**The equation [17] allows the calculation of the reduced tensile strength $T_i$. This equation shows how the tensile strength $T_{i-1}$ just before the corner (tensile strength in the geogrid, going from the bottom to the top of the slope) is reduced to $T_i$ just after the corner. Looking at equation [17] we can note that: a)The shape of the curve can be neglected for the calculation of the tensile forces reduction, b) $T_i$ decreases exponentially with the increment of $\varphi_{min}$ and $\Delta\alpha$. Hence, the more is the friction angle or the change of direction, the more is the reduction.**

**In this model the weight of the column of soil over the curve has been neglected. This simplification can be acceptable because the length of the curve is very small compared with the slope dimensions at both sides of the corner, because the effect of this small column of soil has been considered in the previous analysis (point 2.1) and, furthermore, this additional pressure should increase the friction effect; so we can state that this simplification is on the safe side and does not jeopardize the result (that is much more influenced by other factors like the adoption of the right friction angle value).**

### 2.3 Transmission of the geogrid tensile strength through concave corners and uplift checking

**Geogrids are materials able to bear only tensile stresses, because they lack compression, shear and bending stiffness, this involves that, when are under tension, tends to set out in rectilinear way. If the geogrids under**

**tension turn around a corner mobilize a pressure on it. In our case, in concave corners the pressure is mobilized on the cover soil layer. If the resultant of this pressure has a vertical component it tends to uplift the cover soil.**

**The uplift is a very complex problem but can be analyzed with a simple approach applying the principle of cables carrying an uniform distributed load. The geogrid, carrying the weight of the cover soil layer, should take the shape of a catenary. For small ratios camber/span (1:8 or less) we can approximate the shape of the curve to a parabola, without introducing sensitive error from a practical point of view.**

**The following figure represents a corner in which the input data are: the slope angles $\alpha_{i-1}$ e $\alpha_i$ of both stretches, the tensile force $T_{i-1}$, the cover soil thickness h and its unit weight $\gamma$. The inclination of $T_{i-1}$ is $\alpha_{i-1}$ and the inclination of $T_i$ is $\alpha_I$ with respect to the horizontal. The weight of the cover soil layer can be represented as a uniform vertical surcharge.**

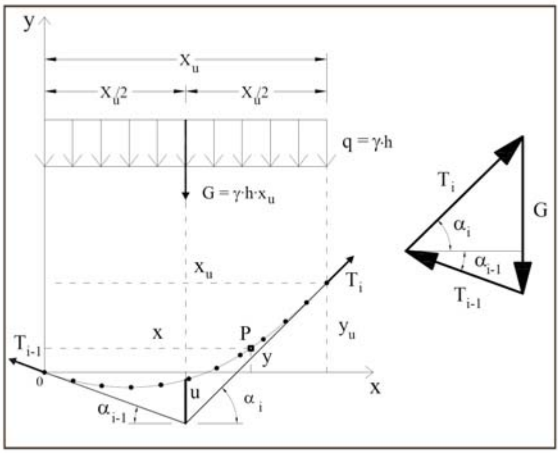



**Figure 5. Scheme of forces in concave corners.**

2.3.1 Determination of the parabola equation

**The geogrid must be in equilibrium under the action of three forces: the weight of the cover soil and the tensile forces $T_{i-1}$ and $T_i$. If we indicate the weight of the cover soil per unit length as $\gamma$. h ; its resultant in the considered stretch "x" is G = $\gamma$. h .x [kN] per 1 meter of depth perpendicular to the plane (the weight of the geogrid is neglected). The direction of the forces $T_{i-1}$ , $T_i$ and G are known, and we can consider that the resultant G is equidistant between the extreme of the considered stretch. For the condition of equilibrium in the plane this forces must intersect in one point. Then we can realize the polygon of forces as indicated in figure 5.**

**Making a relation between similar triangles, we can write:**

$$\frac{y + \frac{x}{2} \cdot \tan \alpha_{i-1}}{\frac{x}{2}} = \frac{\gamma \cdot h \cdot x - T_{i-1} \cdot \mathrm{sen}\alpha_{i-1}}{T_{i-1} \cdot \cos \alpha_{i-1}} \qquad \textbf{[18]}$$

**Developing this formula, the equation of the parabola is:**

$$y = \frac{\gamma \cdot h}{2 \cdot T_{i-1} \cdot \cos \alpha_{i-1}} \cdot x^2 - \tan \alpha_{i-1} \cdot x \qquad \textbf{[19]}$$

2.3.2 Determination of the Tensile force "$T_i$" and the length of the uplifted stretch "$x_u$"

**Applying the equilibrium condition in figure 5:**

$$\sum F_H = 0 \qquad \Rightarrow \qquad T_{i-1} \cdot \cos \alpha_{i-1} - T_i \cdot \cos \alpha_i = 0 \qquad \textbf{[20]}$$

**and**

$$\sum F_V = 0 \qquad \Rightarrow \qquad G - T_i \cdot \mathrm{sen}\alpha_i - T_{i-1} \cdot \mathrm{sen}\alpha_{i-1} = 0 \qquad \textbf{[21]}$$

The tensile force $T_i$, that will be transmitted to the following stretch, can be obtained from [20]

$$T_i = T_{i-1} \cdot \frac{\cos \alpha_{i-1}}{\cos \alpha_i} \quad [22]$$

$$G = \gamma \cdot h \cdot x_u \quad [23]$$

Introducing [22] and [23] in [21], the uplift distance $x_u$ is:

$$x_u = \frac{T_{i-1}}{\gamma \cdot h} \cdot (\cos \alpha_{i-1} \cdot \tan \alpha_i + \mathrm{sen}\alpha_{i-1}) \quad [24]$$

The distance $x_u$ indicates the total stretch subject to uplift, in horizontal projection, distributed in two half of $x_u/2$ for every stretch. Looking at eq. [24] we can note that in concave corners there is always an uplift effect. The thickness of the cover soil should be infinite to get $x_u = 0$ ($x_u \rightarrow 0$ if $h \rightarrow \infty$)

2.3.3 Determination of the vertical uplift "u" in the corner.

Looking the figure 5, the value of "u" can be determined with the following expression:

$$u = y(x_u/2) + x_u \cdot \tan \alpha_{i-1} \quad [25]$$

Where $y(x_u/2)$ is obtained using the eq. [19] for $x = x_u/2$, therefore:

$$u = \frac{\gamma \cdot h \cdot x_u^2}{8 \cdot T_{i-1} \cdot \cos \alpha_{i-1}} \quad [26]$$

Looking at eq. [26] we can note that the uplift "u" is equal to the camber of the parabola.

Therefore, observing the eq. [24] and [26] we can deduct that in concave corners with $T_{i-1} \neq 0$, there is always an uplift effect (even if small) that can not be avoided, but must be limited. This effect can be reduced increasing the thickness "h", the unit weight of the cover soil in that stretch (berm), and/or given a counter inclination to the berm (increasing $\alpha_{i-1}$).

## 3. DESIGN PROCEDURE

This design method presupposes the following simplifying hypothesis: a) the geogrid is inextensible, b) the passive earth pressure at the toe is not considered, c) the friction angle of cover soil $\phi_{soil}$ is higher than the slope inclination $\alpha$ (applying a suitable factor of safety, no sliding surfaces can occur above the geogrid), d) the soil shear strength along vertical slices is neglected, e) the vertical pressure of the cover soil layer on convex corners is not considered.

### 3.1 Ultimate state analysis approach

With the ultimate state analysis the ultimate design strength of the geogrid can be calculated applying suitable factors of safety on the system

3.1.1 Factors of safety

According with the Eurocode 7 (from now EC7), the following factors of safety must be taken into account for design:

3.1.2 3.1.1.1 Design values for geotechnical parameters

Design values for geotecnical parameters ($X_d$) shall either be derived from characteristic values ($X_k$) using the equation:

$$X_d = X_k / \gamma_M \quad [27]$$

**Where $\gamma_M$ is the partial factor for a material property, also accounting for model uncertainties.**

**Equation 27 must be applied to $\gamma_{soil}$ ($\gamma_\gamma$ = 1,00) and to $\phi_{soil}$, $\varphi_{min}$ ($\gamma_\varphi$ = 1,25); this factor is applied to tanφ', in the following way:**

$$\tan\phi_{soil,d} = \frac{\tan\phi_{soil}}{\gamma_\varphi} \qquad [28]$$

3.1.3 3.1.1.2 Design values of actions

**The design values of an action ($F_d$) shall either be assessed directly or shall be derived from representative values using the following equation:**

$$F_d = \gamma_F \cdot F_{rep} \qquad [29]$$

**Where $\gamma_F$ is the partial factor for an action and $F_{rep}$ is the representative value of an action derived from the characteristic value $F_k$ ($F_{rep} = \psi.\ F_k$ ; see EC7). In our case for permanent actions the partial factors are: $\gamma_{G,dst}$ = 1,10 for unfavourable destabilizing driving forces and $\gamma_{G,stb}$ = 0,90 for favourable stabilizing forces.**

3.1.4 Verification of static equilibrium

**Considering the limit state of static equilibrium, it shall be verified that the design value of the effect of destabilizing actions must be less or equal than the design value of the effect of stabilizing actions:**

$$E_{dst,d} \le E_{stab,d} \qquad [30]$$

**In our case, if we perform the limit static equilibrium analysis, the equations that governs the problem became:**

**For rectilinear slope (from eq. [5] and [6])**

$$T_{i-1} + \gamma_{G,dst} \cdot G_T \le \gamma_{G,stb} \cdot F + T_i \qquad [31]$$

$$T_i = (\gamma_{soil} / \gamma_\gamma) \cdot h \cdot x \cdot (\gamma_{G,dst} \cdot sen\alpha - \gamma_{G,stb} \cdot \cos\alpha \cdot \frac{\tan\varphi_{min}}{\gamma_\varphi}) + T_{i-1} \qquad [32]$$

**For convex corners (from eq. [17])**

$$T_i = \frac{T_{i-1}}{e^{(\tan\varphi_{min} \cdot \Delta\alpha)/\gamma_\varphi}} \qquad [33]$$

**For concave corners (no variation of eq. [22])**

$$T_i = \frac{\cos\alpha_{i-1}}{\cos\alpha_i} \cdot T_{i-1} \qquad [34]$$

3.1.5 Design steps

**The calculation is carry out proceeding as follow:**

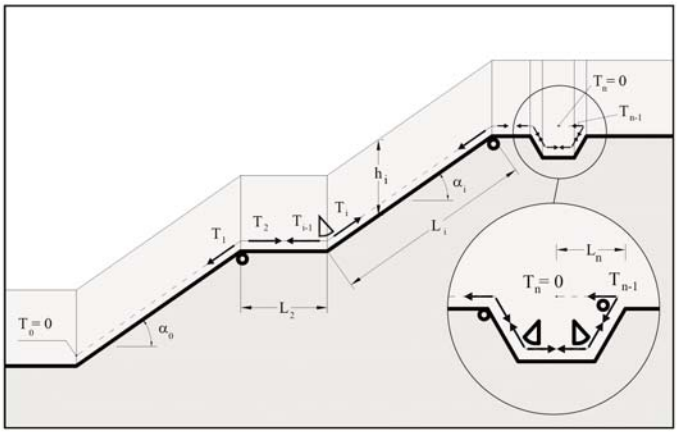



**Figure 6. Scheme of sequence for design procedure.**

**Once defined the geometry of the total slope profile (slopes and berms) and the thickness of the cover soil (that could be modified later, if necessary), the calculation starts covering the multislope system from the bottom to the top, thus the tensile forces in the geogrid are calculated progressively. At first, is necessary to individuate every local situation with its geometric characteristics, that is: stretches, convex corners (circular symbols in fig. 6) and concave corners that induce uplift (triangular symbols in fig. 6). Then, proceed starting from the toe, in which the tensile force in the geogrid is zero ($T_0$=0); going up along the stretch tensile forces in the geogrid increase until the crest of the slope. Just before the corner the tensile strength of the geogrid is calculated according with the equation [32]. The drop of tensile forces in the geogrid due to the convex corner is calculated with equation [33], introducing as input value the tensile strength previously determinated, the angle that define the change of direction $\Delta\alpha$, and the friction angle $\varphi_{min}$. Along the first berm, proceed applying again the equation [32] taking in consideration that the tensile force $T_{i-1}$ is that obtained just after the first corner. If the calculated force $T_i$ is $\leq$ 0, that means that the geogrid does not work and the next slope can be calculated as the first, that is setting up $T_{i-1}$=0; otherwise in coincidence with the concave corner, the tensile force $T_i$ transmitted to the next stretch must be calculated with equation [34]. This procedure must be applied for the rest of the slope and also in the anchor trench. The condition to calculate the final anchor length of the geogrid and thus, the size of the trench is that the tensile force at the extreme of the geogrid must be zero ($T_n$ = 0). The design can be always optimized interacting with the slope geometry.**

**The main question to verify the uplift is to establish which portion of soil cooperates to avoid lifting. One approach is to consider the weight of the cover soil included in the area contained between the spreading angles of (45°+$\phi_{soil}$/2) from both sides (left and right) of the distance $x_u$ (see fig. 5). According to EC7, the following partial factors of safety must be adopted for uplift limit state (UPL) divided in actions and soil parameters: a) Unfavourable (destabilizing) actions $\gamma_{G,dst}$ = 1,00; b) Favourable (stabilizing) actions $\gamma_{G,stb}$ = 0,90; c) Shearing resistance $\gamma_{\varphi}$ = 1,25 (related to tan$\varphi$'); d) Effective cohesion $\gamma_{c'}$ = 1,25, and the apply the condition represented in formula [30].**

**The construction procedure must be taken into consideration during the design phase. In actual fact, during the installation could happen, for a short period of time, critical situations that can lead to instability problems or to overload the reinforcement in particular local points (for instance, due to dynamic loads transmitted by the machines during installation). In multislopes systems made with continuous reinforcements, the cover soil must be, at first, laid on the horizontal surfaces (berms) and in the anchor trench, in order to fix the geogrid and avoid lifting problems. Therefore, in the design is necessary to state the installation sequence checking those short term loading situations during the construction phase that could be more critical than the final load configuration. In these cases the allowable tensile strength of the geogrid can be considered higher than that considered for long term because of the less influence of creep in the reinforcement**

### 3.1.6 Trench tooth verification

**The high tensile stresses hold by the geogrid could generate a failure shear plane in the trench tooth. Hence, is necessary to check if the tooth is wide enough, at its base level, in order to avoid failure due to shear stresses.**

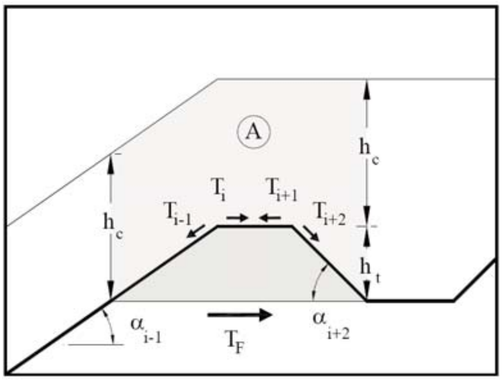


**Figure 7. Scheme of forces in the tooth of the trench.**

$$G = A \cdot (1m) \cdot \gamma \qquad [35]$$

**A = area of cover soil above the shear plane [$m^2$]**

**$T_F$ = Shear resistance of the soil (stabilizing action) that try to avoid the sliding [kN/m]**

**$T_S$ = Driving shear forces (destabilizing action) that try to cut the tooth [kN/m]**

**The condition that must be fulfilled is:**

$$T_{i-1} \cdot \cos\alpha_{i-1} - T_i + T_{i+1} - T_{i+2} \cdot \cos\alpha_{i+2} \le \left( \frac{\gamma_{G,stb}}{\gamma_\gamma \cdot \gamma_\varphi} \right) \cdot G \cdot \tan\varphi_{soil} + (T_{i-1} \cdot \mathrm{sen}\alpha_{i-1} + T_{i+2} \cdot \mathrm{sen}\alpha_{i+2}) \cdot \tan\varphi_{soil}/\gamma_\varphi \qquad [36]$$

### 3.2 Serviceability state analysis

**The serviceability state analysis can be useful to check the deformation in the system, particularly regarding the uplift in concave corners. To perform this analysis can be applied the same equations used for the ultimate state analysis setting all factors of safety equal to one (FS=1).**

**The equations [24] and [26] give the values of uplifting. As demonstrated above, when $T_i > 0$, $x_u$ is always different than zero, so the problem is to fix an allowable value of $x_u$ and "u" to prevent uplift. These critical values need to be investigated exhaustively by means of trials. In this paper is suggested to not exceed the worst case between the following limits: a) $x_u/2$ (eq. [24]) must be < 5% of the minimum length between the stretch before and after the considered corner; b) The uplift height "u" (eq. [26]) must be < than the 5% of the cover soil thickness h; c) The tensile force $T_{i-1}$ should not increase more than 5% due to the shortening of slope distance ($x_{i-1}$-$x_u/2.\cos\alpha_{i-1}$). If this limits are not fulfilled, is possible to reach it increasing the cover soil thickness and/or the counter inclination of the berm and/or using in the corner a material with higher unit weight.**

## 4. PERFORMANCE REQUIREMENTS OF REINFORCEMENT GEOGRIDS

**In this particular application geogrids works as "violin strings", that is, are subjected at high tensile forces from the beginning until the whole life. For this reason, the correct functioning of the geogrid and, what is more important, the safety level of the system, depends directly on its technical characteristics. The relevant characteristics that a reinforcement geogrid must fulfil to guarantee a good performance are:**

### 4.1 Technical characteristics:

**a) Low strain at short and long term (low creep): the deformation must be limited to avoid the transmission of tensile forces to the liner, with particular regard during the design life. The right way to know the effect of creep and relaxation in the geogrid and, therefore, the reduction of the stiffness modulus of the geogrid, is through**

**the isocronus curves that must be demanded to the producer. Geogrids that fulfil this requirement are normally made with high modulus polyester or PVA.**

**b) Ultimate Design Tensile Strength: is an essential requirement to know the UDTS applying "certified" reduction factors on the ultimate tensile strength due to creep, installation damage, environmental attack, extrapolation value, etc. according with the adopted standard.**

**c) Chemical Resistance: particular attention on the reduction factor for environmental attack must be taken in consideration when the geogrid is used in landfill in direct contact with leach.**

**d) Interface friction angle: The friction angle between soil-geogrid and other contact surfaces (liner, drainage geocomposites) must be known, as well as the behaviour of the geogrid under pull out to check the sliding and pull out effect during the design.**

### 4.2 Geometrical characteristics of the geogrid:

**a) Proper shape for soil interlocking: to ensure the transmission of driving forces from the cover soil to the geogrid, the soil particles must interlock with it; for this reason the geogrid must be separated from the bottom surface. This gap can be reached using three dimensional grids or proper spacers.**

**b) Geogrid continuity: the geogrid must be uninterrupted along the slope. To guarantee the continuity in forces transmission, longitudinal overlaps are not allowed.**

**c) Width of the geogrid: wide geogrids help to reduce waste of material, mainly along curved sectors, and reduce the installation time.**

## 5. CONCLUSION

**This paper has analysed the stability of cover soils placed on smooth inclined multislopes sections in which the soil layer is hold by an unique and continuous geogrid reinforcement. This configuration allows to avoid the realization of anchor trenches at every berm and to interrupt the geogrid continuity. The change of direction in every vertex is considered in the transmission of tensile forces in order to represent the actual situation. Future investigation by means of trials are necessary to understand better the uplift effect in concave corners in order to get ready the analytical model.**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