

# A NEW CALCULATION APPROACH TO DESIGN FLEXIBLE FACING SYSTEM FOR SOIL NAILING

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## ABSTRACT

According to the experience of several researchers, under certain conditions the soil nailing facing system can be developed with nails in cooperation with steel mesh (i.e. flexible structural facing). The goal of this system is to improve the slope face stability and allow the vegetation to grow. A simple design approach was introduced a few years ago that analysed the behaviour of the mesh by comparing the maximum volume of debris that can move among the nails to the maximum volume that can be held by the mesh. Even if it took into account the real interaction between mesh and soil, such procedure was quite rudimentary by solving the non-linearity of the load - displacement problem. Recently, a new design approach using forces generated by the soil pushing on the mesh was proposed considering the most unfavourable case between the two wedge analysis and the single wedge, one for slope failure mode (according to the standard BS 1006 – 2010). Concerning the mesh resistance, the new approach overcomes the non-linearity of the problem and allows a more realistic calculation approach. This has been feasible thanks to the interpretation of the load-displacement curves generated in accordance to the UNI 11437 (2012) Standard as well as to the introduction of the “scale effect” that modifies the nail spacing and mesh behaviour accordingly.

For sure the methodology is not perfect, but at least it allows appreciating the Ultimate Limit State and the Serviceability Limit State with a simple calculation. This paper analyses the main calculation steps and concepts of this new approach implemented in the new Bios 2 software which is used by Maccaferri for the design of flexible facing of cut and natural slopes.

## 1 INTRODUCTION

The use of steel mesh for facing soil nailed slopes has increased considerably within the last few years. The system, known in the technical literature as Flexible Facing (Phear et al., 2005), has, without doubt, some advantages for its natural aesthetic appearance where it can be used to successfully stabilize slopes with vegetation. Whereas the design of the nails is well known and used in practice, the design analysis of the mesh facing is less known. In the past Giacchetti et al. (2011) suggested an initial design approach for such facings in order to improve industry understanding of the use of meshes. That approach highlighted that a proper design has to consider the resistance as well as the deformation of the meshes, and introduced criteria for serviceability. The purposed approach – named BIOS (Best Improvement of Slopes) - was quite rudimentary since it was simply based on the comparison between volume of soil that potentially could move among the nails, and the maximum volume of soil that could deform or reach the ultimate resistance of the mesh. The present paper completely reviews the BIOS approach on the basis of better knowledge of the meshes under deformation loads and presents a new approach to design flexible facing system for soil nailing.



Figure 1: Soil nailing example of soil nailing with hexagonal mesh and steel rope panel or facing

## 2 THE CONCEPT OF SOIL NAILING

The aim of soil nailing is to improve soil stability when there are unfavourable stability conditions. The stability is achieved by inserting reinforcement bars into the soil, which are then grouted and fixed soundly to the ground for their entire length (nailing). As the nail is not tensioned, it has a “passive” behaviour and mobilizes friction forces along the entire length when there are displacements in the soil (Schlosser et al., 2002; Soulas R., 1991; BS 8006; Byrne, et al., 1998). The frequency and the length of the nails must be calculated in accordance with the criteria suggested in many codes (example: BS 8006; EN 1997-1; Government of Hong Kong, 2008, FHWA) and specifications (example: NCHRP REPORT 701 - Lazarte, 2011). The protection of the exposed surface of the soil reinforced by the nails is obtained with a facing, the aim of which is to retain the soil between the nails, prevent erosion phenomena and assume an aesthetic function. The facing obviously must interact with the passive action of the nails.

## 3 HOW FLEXIBLE FACING WORKS

Phear (2005) and BS 8006-2 (2011) suggest that on slopes of up to approximately 60° the facing may also be made with flexible structures (Flexible Facing – wire mesh or wire mesh geocomposites); the preferential field of application of the flexible facing is on natural slopes or on relatively small excavated faces, where significant variations in the applied stresses are not expected.

Experience shows that the facing provides passive restraint (Turner, 2012) despite any construction effort: on one hand placing the mesh in continuous contact with the soil is not possible because of the surface morphology (Ferraiolo and Giacchetti, 2004), on the other hand pre-tensioning of the mesh by means of nail plates does not offer any advantage because the forces are short circuited just below the plate. (Giacchetti et al., 2011). For this reason, the flexible facing can never be considered as a structural fit to allow perfect cooperation between nails, especially when their spacing is wider than 1.5 m (5 ft). The flexible nature of the meshes means that the ground surface can deform and push on the facing, which will then allow formation of pockets of debris (Figure 2).



Figure 2: Large pockets of debris pushing on the facing and deforming the mesh.

Based on the author’s experiences and the technical literature, the main properties of the meshes are the weight per unit area, the resistance to- and related deformability under tensile and punch testing. Various studies and laboratory tests have been carried out with regard to the behavior of the meshes using various sized samples fastened to test frames with a range of constraint conditions. (Ruegger., & Flumm, 2000; Bonati & Galimberti 2004; Torres et al., 2000; Muhunthan et al., 2005, Bertolo et. al. 2007; Bertolo et. al., 2009). The results of the research highlight that the movement of meshes subject to punching ranges from tens of centimetres (a few inches) up to one meters (feet), with a non-linear development of response, the trend of which depends mainly on the combination of the mesh weave, the size of the test sample and the type of constraint with which the sample is fixed during testing. During the initial phase of loading, large displacements have been observed in all the tests. Then the mesh starts to appreciably resist the load.

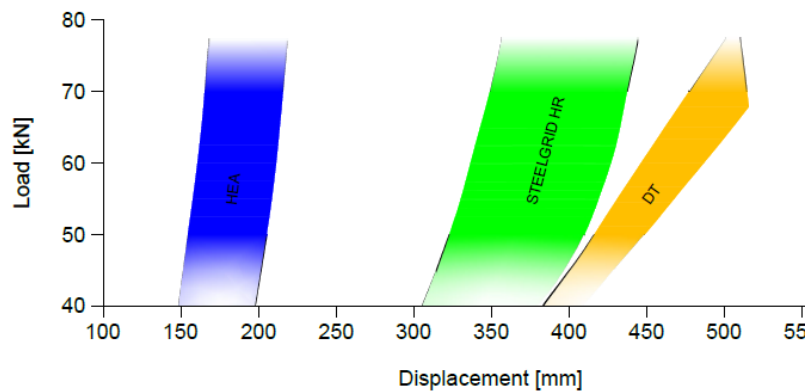


Figure 3: Comparison between the load-displacement curves of different mesh types subject to punch tests

Given this behaviour, one of the more relevant problems while in a soil nailing system consists of identifying the most cost effective mesh aimed at reducing the deflection of the facing: for example, with the stiffer meshes available on the market and according to lab experience, it is advisable to consider samples  $3 \times 3$  m ( $10 \times 10$  ft) fastened on all sides. The doubletwist wire mesh reinforced with steel cables (Steel-grid) is more deformable compared with the wire rope panel (see Figure 3), but more rigid than the single-twist meshes with high strength wire (IUAV, 2012). The Italian Standard UNI 11437 (2012) Rockfall protection measures: Tests on meshes for slope coverage has introduced a new test method that can be used to design flexible facing, as it is the first worldwide testing guideline that describes the procedure for punch resistance testing of meshes. The standard is carried out with samples having a size of  $3.0 \times 3.0$  m ( $10\text{ft} \times 10\text{ft}$ )  $\pm 20\%$ , restrained into a rigid frame and loaded by means of a punching device with a diameter of 1.0 m (3 ft) (see Figure 4). This procedure is the first full scale test that allows direct comparison between different kinds of mesh (i.e.: double twist, single twist, ring net, cable panel and so on) and accordingly the choice of suitable mesh types.

Since the test generates a typical graph load vs. deformation curve, a design approach considering Ultimate and Serviceability approaches for the structure is becoming possible. For example (Figure 2), a large deformation implicates conditions of potential stripping of the nails or an incipient rupture of the mesh (ultimate limit state). If the facing is slightly deformed, the pocket of debris should be removed before the mesh is irreversibly damaged (serviceability limit state).

Estimation of the deformation is not simple because the spacing between the nails could vary from the size and arrangement of the standard punch test (example: sample  $3.0$  m  $\times$   $3.0$  m ( $10$  ft  $\times$   $10$  ft); with the field spacing of nails at  $1.5$  m  $\times$   $1.5$  m ( $5$  ft  $\times$   $5$  ft). In that case the test carried out in accordance with UNI 11437 (2012) is not fully representative of the full scale test and real mesh behaviour, and in this case a correction may be necessary. It is possible to assert that the larger the sample size, the larger the displacement will be, and also the larger the sample is, the larger the punch resistance will be. This principle is named the scale effect of meshes. The general law of the scale effect is assumed in the following simplified form referring to the coordinates of the load-displacement diagrams (Figure 5):

$$x = x_0 \cdot \mu_x \quad (1)$$

$$y = y_0 \cdot \mu_y \quad (2)$$

Where:

$(x, y)$  = generic coordinate of the scaled graphic.

$(x_0, y_0)$  = generic coordinate of the reference graphic.

$(\mu_x, \mu_y)$  = constants correlating the scale to the reference graphic, that depend on the mesh type.

The constants  $(\mu_x, \mu_y)$  are scale coefficients that correlate the mechanical behaviour of the net as a function of the sample dimensions (the distance between the nails on the jobsite application). Maccaferri has been able to get reliable values because of the large amount of data they have collected during many tests.

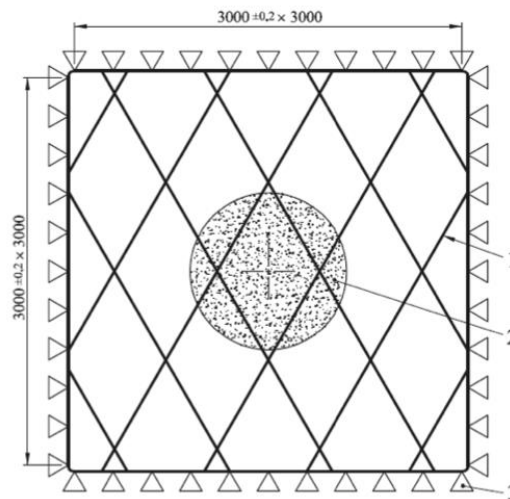


Figure 4: Plan view of the punch test according to UNI 11437:2012. Legenda: 1 = tested mesh; 2 = punching device (1.0 m (3 ft) in diameter); 3 = perimeter constraint between the mesh and the frame

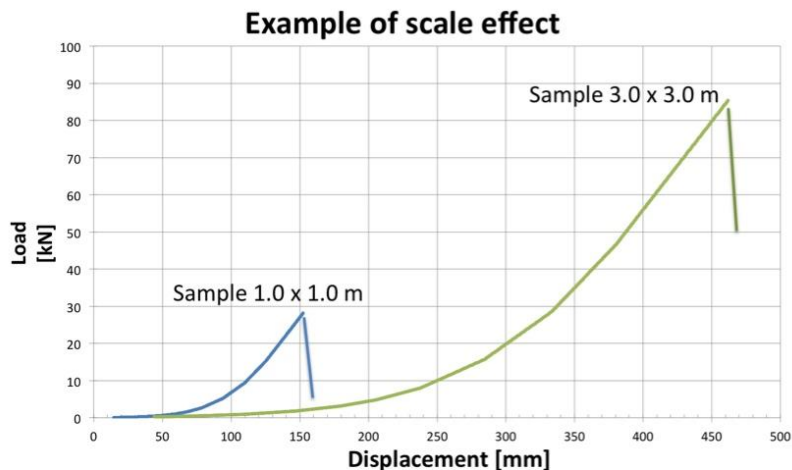


Figure 5: Graph Displacement VS Load with the typical scale effect in the punch test

#### 4 SIMPLIFIED APPROACH TO DESIGN FLEXIBLE FACING: BIOS

Below are described the calculation steps proposed by the authors to design soil nailing flexible facing. This methodology is adopted by Maccaferri and is implemented in the software BIOS.

The software analyses only the behaviour of the net, evaluating the average spacing of nails as given.

The analysis is divided into 4 steps:

1. **Short term analysis:** the stretch of the slope between two nails is analysed, which must have a safety factor not less than 1.0. In fact, if not at equilibrium it is not possible to install the net. So the adequacy of the nail spacing in relation to the geotechnical properties of the soil is verified. If limit equilibrium is not satisfied, it is necessary to decrease the spacing between the nails. To ensure stability without the flexible structural facing, the analysis is done with two different approaches: a single wedge method and a two wedge method. The minimum value of safety factor ( $FS_{min}$ ) obtained from the two methods is compared with the limit equilibrium value of 1.0; if  $FS_{min}$  is greater than this value you can proceed with the next steps.

The characteristic values of resistance of the soil have been used because the calculation concerns a temporary condition and the *geotechnical safety coefficient*  $\gamma_\phi$  (friction angle) and  $\gamma_c$  (cohesion) *are not taken into account*. If there are serious uncertainties, the designer can insert the project's resistance values, which are equal to the characteristic values conveniently reduced by the safety factors (e.g. for Eurocode 7  $\gamma_\phi$  (friction angle) and  $\gamma_c$  (cohesion) *are both equal to 1.25*).

For the same reason, in this phase seismic loading is not taken into account.

2. Long term analysis: the aim of this analysis is to evaluate the load on the net facing suspended between the anchors. For this reason, in accordance with the British Standard 8006-2:2011 and CIRIA 637 procedures, the geotechnical parameters that characterize the soil have been reduced assuming that the ground conditions decay to the residual resistance (close to rupture). The parameters are defined as:

- $c'$  (residual cohesion) = 0;
- $\phi_a'$  (friction angle) = residual friction angle of the soil.

Therefore the debris friction angle  $\phi_a'$  will be equal to the residual friction angle of the soil in examination. In absence of experimental data, it is suggested to use a value equal to  $\phi_a' = \phi'/2$ .

The calculation procedure for the load acting on the facing is conducted, according to the BS 8006-2 procedure with reiterative analysis using the method of the two wedges (with possible seismic load). This calculation method maximizes the force acting on the net analysing every geometrical configuration of the two wedges (combinations of angles  $\varepsilon_1$  and  $\varepsilon_2$  - see Figure 32 BS 8006-2).

3. Ultimate limit state check: the forces, calculated in the previous step, are compared with the punching resistance of the net which is obtained from standardized laboratory tests (UNI 11437: 2012) appropriately modified in order to consider the scale effect. The check is satisfied if the resistance of the net is greater than the pressure of the soil.
4. Serviceability limit state check: this analysis checks whether the deformations of the flexible facing induced by the soil are acceptable. If the forces are evaluated as excessive, a stiffer mesh type, or narrower anchor spacing are required. The procedure is based on the graphics of punching test UNI 11437: 2012 appropriately modified because of the scale effect.

#### 4.1 SHORT TERM ANALYSIS

The short term solution is divided in two sub-analysis; in particular two wedges are analysed (Figure 6) and along with a one wedge (Figure 7) mechanism of failure to consider every possible collapse. The minimum value of safety factor obtained from the two methods is compared with the limit value of 1.0:

$$FS = \min(FS_{\text{ONE WEDGE}}; FS_{\text{TWO WEDGES}}) > 1.00 \quad (3)$$

##### Two wedges method

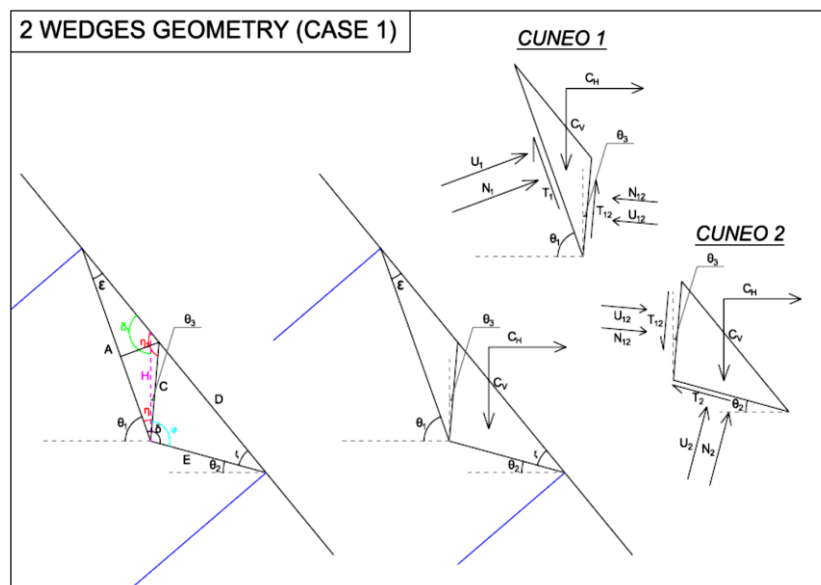


Figure 6: Two wedges mechanism of failure

The analysis is carried out evaluating the forces acting on the two wedges faces and the value of the safety factor (FS). You get 4 equations of equilibrium to the translation (vertical and horizontal) for each wedge, and 3 equations of the tangential stress  $T_i$  function of the safety factor:

$$\begin{cases} \sum x^{(1)} \\ \sum y^{(1)} \end{cases} \quad \begin{cases} \sum x^{(2)} \\ \sum y^{(2)} \end{cases} \quad (4)$$

$$T_1 = \frac{[c_1^I \cdot l_1 + (N_1 - U_1)\tan(\varphi_1^I)]}{FS} \quad (5)$$

$$T_2 = \frac{[c_2^I \cdot l_2 + (N_2 - U_2)\tan(\varphi_2^I)]}{FS} \quad (6)$$

$$T_{12} = \frac{[c_{12}^I \cdot l_{12} + (N_{12} - U_{12})\tan(\varphi_{12}^I)]}{FS} \quad (7)$$

The expanded system is shown below:

$$\begin{cases} N_1 \cdot \sin(\theta_1) - T_1 \cdot \cos(\theta_1) + T_{12} \cdot \sin(\theta_3) - N_{12} \cdot \cos(\theta_3) + F_{X1} = 0 \\ F_{Y1} - N_1 \cdot \cos(\theta_1) - T_1 \cdot \sin(\theta_1) - T_{12} \cdot \cos(\theta_3) - N_{12} \cdot \sin(\theta_3) = 0 \\ N_2 \cdot \sin(\theta_2) - T_2 \cdot \cos(\theta_2) - T_{12} \cdot \sin(\theta_3) + N_{12} \cdot \cos(\theta_3) + F_{X2} = 0 \\ F_{Y2} - N_2 \cdot \cos(\theta_2) - T_2 \cdot \sin(\theta_2) + T_{12} \cdot \cos(\theta_3) + N_{12} \cdot \sin(\theta_3) = 0 \\ T_1 - \frac{1}{FS} [c'_d \cdot A + (N_1 - U_1) \cdot \tan(\varphi'_d)] = 0 \\ T_2 - \frac{1}{FS} [c'_d \cdot E + (N_2 - U_2) \cdot \tan(\varphi'_d)] = 0 \\ T_{12} - \frac{1}{FS} [c'_d \cdot C + (N_{12} - U_{12}) \cdot \tan(\varphi'_d)] = 0 \end{cases} \quad (8)$$

where:

$$c'_d = \frac{c'}{\gamma_{cr}}$$

$$\varphi'_d = \tan^{-1} \left( \frac{\tan \varphi'}{\gamma_{\varphi'}} \right)$$

$a_v$  = average spacing between the nails

$\beta$  = slope angle

$\gamma$  = self-weight of the soil

$r_u$  = pore pressure coefficient

$$\xi = \beta - \theta_2$$

$$\varepsilon = \theta_1 - \beta$$

$$\delta = \pi - \theta_1 + \theta_2$$

$$\eta = \frac{\pi}{2} - \theta_1 + \theta_3$$

$$\eta_1 = \pi - \eta + \varepsilon$$

$$\psi = \delta - \eta$$

$$\delta_1 = \pi - \varepsilon - \eta + \theta_3$$

$$E = a_v \cdot \frac{\sin(\varepsilon)}{\sin(\delta)}$$

$$A = a_v \cdot \frac{\sin(\xi)}{\sin(\delta)}$$

$$C = A \cdot \frac{\sin(\varepsilon)}{\sin(\eta_1)}$$

$$D = C \cdot \frac{\sin(\psi)}{\sin(\xi)}$$

$$H = A \cdot \frac{\sin(\varepsilon)}{\sin(\delta_1)}$$

$$h_1 = C \cdot \sin(\eta)$$

$$\text{Area}_1 = \frac{1}{2} \cdot h_1 \cdot A$$

$$h_2 = C \cdot \sin(\pi - \eta_1)$$

$$\text{Area}_2 = \frac{1}{2} \cdot h_2 \cdot D$$

$$W_1 = \gamma \cdot \text{Area}_1$$

$$W_2 = \gamma \cdot \text{Area}_2$$

$$U_1 = \frac{1}{2} \cdot \gamma \cdot r_u \cdot H \cdot A$$

$$U_2 = \frac{1}{2} \cdot \gamma \cdot r_u \cdot H \cdot E$$

$$U_{12} = \frac{1}{2} \cdot \gamma \cdot r_u \cdot H \cdot C$$

$$F_{X1} = U_1 \cdot \sin(\theta_1) - U_{12} \cdot \cos(\theta_3)$$

$$F_{X2} = U_2 \cdot \sin(\theta_2) + U_{12} \cdot \cos(\theta_3)$$

$$F_{Y1} = W_1 - U_1 \cdot \cos(\theta_1) - U_{12} \cdot \sin(\theta_3)$$

$$F_{Y2} = W_2 - U_2 \cdot \cos(\theta_2) + U_{12} \cdot \sin(\theta_3)$$

Solving the system we get a single cubic equation yielding the unknown parameter FS (safety factor):

$$a_1 \cdot \text{FS}^3 + a_2 \cdot \text{FS}^2 + a_3 \cdot \text{FS} + a_4 = 0 \quad (9)$$

The expanded equation is shown below:

$$\left\{ \frac{F_{Y1} - \left[ \frac{1}{\text{FS}} (c'_d \cdot A - U_1 \cdot \tan(\varphi'_d)) \right] \cdot \sin(\theta_1) - \left[ \frac{1}{\text{FS}} (c'_d \cdot C - U_{12} \cdot \tan(\varphi'_d)) \right] \cdot \cos(\theta_3) - N_{12}(\text{FS}) \cdot \left[ \sin(\theta_3) + \frac{\tan(\varphi'_d) \cdot \cos(\theta_3)}{\text{FS}} \right]}{\left[ \cos(\theta_1) + \frac{\tan(\varphi'_d) \cdot \sin(\theta_1)}{\text{FS}} \right]} \right\} \cdot \left[ \sin(\theta_1) - \frac{\tan(\varphi'_d) \cdot \cos(\theta_1)}{\text{FS}} \right] - \left[ \frac{1}{\text{FS}} (c'_d \cdot A - U_1 \cdot \tan(\varphi'_d)) \right] \cdot \cos(\theta_1) + \left[ \frac{1}{\text{FS}} (c'_d \cdot C - U_{12} \cdot \tan(\varphi'_d)) \right] \cdot \sin(\theta_3) - N_{12}(\text{FS}) \cdot \left[ \cos(\theta_3) - \frac{\tan(\varphi'_d) \cdot \cos(\theta_3)}{\text{FS}} \right] + F_{X1} = 0 \quad (10)$$

where:



$$FS = \frac{K_1 + K_2 + (W^\perp - U_1^\perp + U_2^\perp) \tan \varphi'_p}{W^{\parallel} - U_2^{\parallel}} \quad (18)$$

Where:

$W^\perp$  (kN) Weight of wedge perpendicular to the sliding surface;

$W^{\parallel}$  (kN) Weight of wedge parallel to the sliding surface;

$K_1$  (kN) Cohesion force acting at the top of wedge;

$K_2$  (kN) Cohesion force acting at the base of wedge;

$U_1^\perp$  (kN) Resultant of the pressure of the water acting perpendicular to the sliding surface;

$U_2^{\parallel}$  (kN) Resultant of the pressure of the water acting parallel to the sliding surface;

$\varphi_d$  (°) Design friction angle of debris;

The minimum FS has to be found solving the equation for each value of the angle  $\vartheta_1$  ( $0 < \vartheta_1 < \beta$ ) and selecting the safety factor with minimum value.

#### 4.2 LONG TERM ANALYSIS

The analysis calculates the forces acting on structural flexible facing according to BS 8006-2.

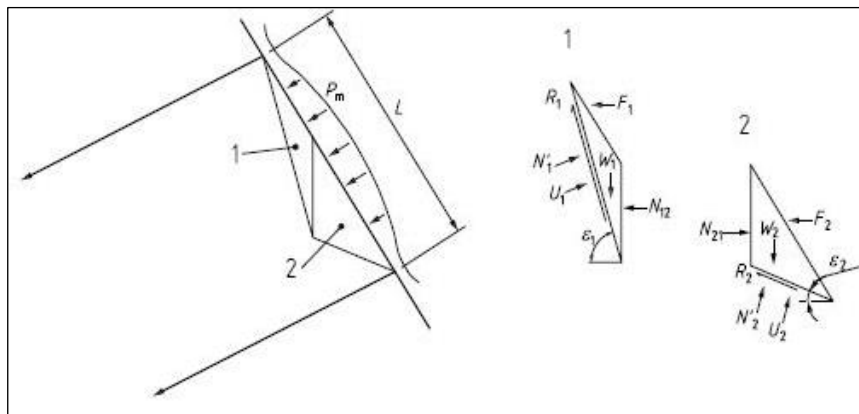


Figure 8: Calculation of design loading acting on a simple flexible facing (taken from BS 8006-2 Figure 32)

In the seismic case, the load acting on the net is equal to:

$$F_1 + F_2 = \frac{W_1(\tan \varepsilon_1 - \tan \varphi_a) + W_1 C_V(\tan \varepsilon_1 - \tan \varphi_a) + \frac{U_1 \tan \varphi_a}{\cos \varepsilon_1}}{1 + \tan \varepsilon_1 \tan \varphi_a} + \frac{W_2(\tan \varepsilon_2 - \tan \varphi_a) + W_2 C_V(\tan \varepsilon_2 - \tan \varphi_a) + \frac{U_2 \tan \varphi_a}{\cos \varepsilon_2}}{1 + \tan \varepsilon_2 \tan \varphi_a} + C_H(W_1 + W_2) \quad (19)$$

Where:

$W_1$  (kN) Weight of wedge 1;

$W_2$  (kN) Weight of wedge 2;

$\varepsilon_1$  (°) Angle at the base of wedge 1;

$\varepsilon_2$  (°) Angle at the base of wedge 2;

$U_1$  (kN) Resultant of the pressure of the water acting at the base of wedge 1;

$U_2$  (kN) Resultant of the pressure of the water acting at the base of wedge 2;

$\varphi_a$  (°) Design friction angle of debris;

$C_V$  Vertical seismic acceleration coefficient;

$C_H$  Horizontal seismic acceleration coefficient;

The calculation method maximizes the force acting on the net analysing every possible geometric configuration of the two wedges (combinations of angles  $\varepsilon_1$  and  $\varepsilon_2$  - see Figure 8).

This procedure is in favour of safety because it always considers the worst sliding surface from a structural point of view. In fact, in reality it may establish sliding surfaces that cause an action on the net less than that calculated.

### 4.3 LONG TERM ANALYSIS

The load, determined in the calculation step number 2, is increased with a safety coefficient that takes into account the uncertainties of the geotechnical model ( $F_{TOT,Design} = (F_1+F_2) \times \gamma_{DF}$ ).

The limit load tolerated by the net ( $F_{lim}$ ) is directly estimated from the characteristic curve of the punching test.

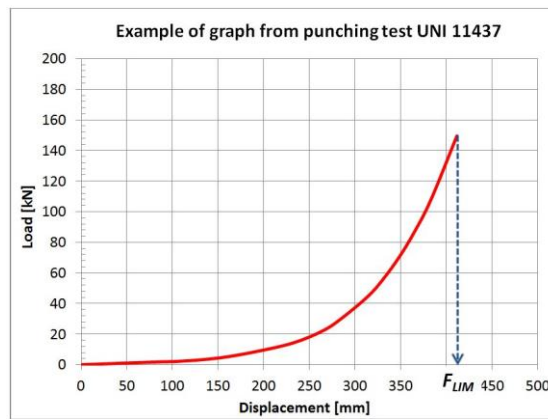


Figure 9: Punching test graph according to UNI 11437 (2012)

The condition is:

$$F_{TOT,Design} < F_{lim} \quad (20)$$

### 4.4 SERVICEABILITY LIMIT STATE CHECK

In the serviceability limit state, the deformation of the net is checked. In fact, to permit the normal operation of the infrastructure protected by the net, we have to control deformation.

The value of deformation ( $\Delta h_d$ ) is obtained from the characteristic graph of the punching test. This value is amplified to take into account the slope irregularities and the installation anomalies:

$$F_{TOT,Design} \cdot \gamma_{BULG} \rightarrow \Delta h_d \quad (21)$$

Where  $\gamma_{BULG}$  is the amplifying coefficient that takes into account the slope irregularities. This value should never be less than 1.5.

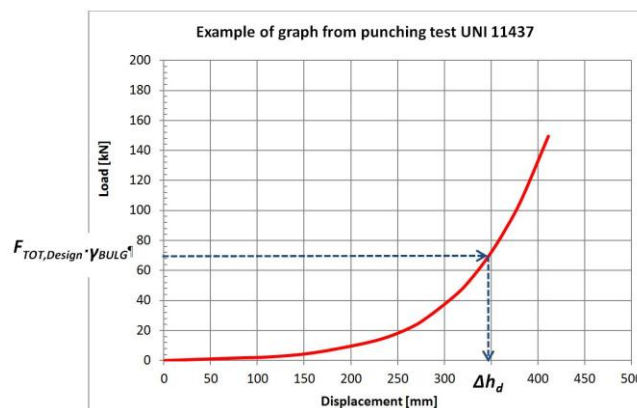


Figure 10: Punching test graph according to UNI 11437 (2012)

An additional displacement value is added to  $\Delta h_d$  due to the assumed inaccuracy of net installation ( $\Delta h_{\text{error}}$ ):

$$\Delta h = \Delta h_d + \Delta h_{\text{error}} \quad (22)$$

If the net is not installed to be perfectly adhering to the slope and it is not well stretched, you might have additional displacement, because the net deforms before starting its sealing function because it is loose. Recommended values of  $\Delta h_{\text{error}}$  range from 0.20 m (8 inches) to 0.35 m (14 inches).

The final check compares the allowable deformation with the value obtained above ( $\Delta h$ ).

The result must be that:

$$\Delta h < \text{Limit Bulging} \quad (23)$$

When deformation exceeds the project limits, the net is not broken, but there is necessary maintenance such as emptying the net, anchor plates tightened, and cable grid installation to stiffen the flexible facing.

## 5 CONCLUSION

The design theory presented herein proposes a simplified procedure aimed at designing flexible facing with steel meshes in concert with soil nailing. The procedure is based on a limit equilibrium method and the punch tests standard UNI 11437: 2012. The procedure improves and upgrades the previous version of the BIOS software developed by Maccaferri, and allows calculating a solution where there are several unknown variables or data and represents a more sophisticated approach. Finally, the designer can choose the most effective solution among a considerable range of conditions with less time-consuming analyses. The approach highlights the fact that the fundamental property for this type of solution is the membrane stiffness of the flexible facing, while its tensile strength has limited influence because the forces at work are generally very low. However, it must be stressed that the designer's judgment is always required in order to verify the conditions in which the facing is to be applied, and identify the general geotechnical conditions that drive a successful stabilization. Further testing and development may be required to better understand the interaction between flexible facings and anchor plates.

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