

Design of simple drapery mesh for rock cuts and natural slopes

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ABSTRACT

Simple drapery mesh (or simple drapery system) is commonly installed to provide rockfall protection in open pit mines or along highways and railways. It is generally used for rock cuts or natural rock faces. The system is a fast and cheap measure against rockfall hazards, and it consists of a steel mesh fixed at the top of the slope with anchors and a longitudinal suspension cable. This paper describes a new design approach (called MacRo 2) to define all the components of the system. A case study in Québec (Canada) is presented.

RÉSUMÉ

Le revêtement simple avec treillis (ou revêtement simple en paroi) est normalement installé pour la protection de chute de pierres dans les mines à ciel ouvert ou le long des autoroutes et des chemins de fer. Il est généralement utilisé dans les excavations en roche ou dans les parois rocheuses naturelles. Le système, qui est économique et très facile à installer, est composé d'un treillis en acier fixé au sommet de la paroi avec des ancrages et un câble de rive. L'article présente une nouvelle approche de calcul (MacRo 2) pour la conception de tous les éléments du système. Un cas d'étude au Québec est présenté.

1 INTRODUCTION

The natural process of weathering generates geological instabilities that frequently expose mining areas, and infrastructures to a wide range of shallow instabilities, which may vary from erosion to rockfalls. Although they mostly cause small size failures, the shallow instabilities cannot be underestimated because they usually happen with high frequency on large surfaces. Consequently, the probability of accidents is high. In this situation, designs must necessarily guarantee the efficiency of the remedial solution in terms of high performance and low maintenance costs. Although technical literature provides many example based on analytical and empirical observation (i.e. Muhunthan and al., 2005), it does not seem possible to codify a common design procedure for all mesh types. In this sense, the designer's experience is always needed in order to evaluate a cost effective intervention.

2 SIMPLE DRAPERY MESH

2.1 System description

A simple drapery mesh (or simple drapery system) consists of a rockfall net along rock slopes (i.e. rock cuts or natural faces). The drapery is hung as a curtain, suspended by a longitudinal rope and anchors at the crest (Figure 1). The distance between the anchors depends on the design and the prevailing instability conditions at the site. The anchors are commonly aligned and fitted with suitable terminations (often eye nuts or plates or similar) to accept the crest rope. The top supports are generally steel bars (full or hollow core) or flexible cable anchors (with single or double leg). In both

cases, the anchors are placed in drilled-holes and then fully grouted along their entire length. The supports are considered passive, because do not require any pre-tensioning, and they start to work only if they are stressed by the loads acting on the mesh.

Once the crest anchors and the upper longitudinal cable are installed, the mesh can be fixed to them and left free all along the slope.

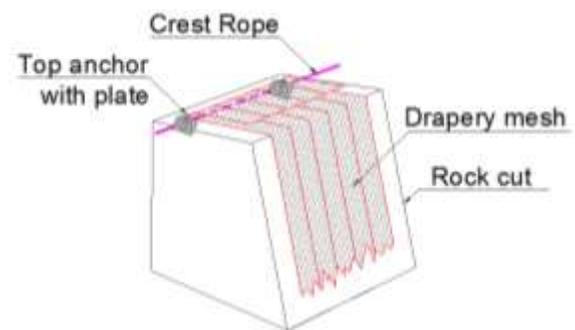


Figure 1. Sketch of a simple drapery system application.

The system may be secured at the toe of the rock cut as well, in order to form a sort of "pocket" where the debris and the rocks may be pile up after their fall (Figure 2). Otherwise, in order to reduce the stress on the mesh, as well as the maintenance costs, the bottom of the mesh can be left opened. In this second case, a ditch (Figure 3) or a barrier is required to collect or contain the fallen materials.

The effect of this kind of intervention is to control the falls of the rocks and debris, which are driven toward the bottom with slow velocity and reduced energy. In comparison to other types of rockfall interventions, they

are simpler to install, cheaper, and their maintenance is easier. Nevertheless, they cannot be considered as a remediation for shallow instabilities.



Figure 2. Debris and rock piled up at the bottom of a simple drapery system fixed at the toe of the slope by anchors and a down-slope longitudinal cable.



Figure 3. Example of a simple drapery mesh with a ditch (highlighted with the yellow line) at the base to collect the debris falling from the slope.

2.2 Limit of the application

The rockfall remedial measures may be grouped into two main categories, which depend on their functionality:

- Active protection systems: they are applied directly on the instable zone in order to prevent or control the movement of the shallow instability. For instance, inside this category there are secured (or pin) drapery systems and pre stressed anchors (tie back anchors).
- Passive protection systems: they do not affect the source area, but they mitigate the instabilities' effects by arresting the trajectories or reducing their falling velocity and energy. They are generally applied far from the detachment area. This category typically includes rockfall and debris flow barriers, embankments and hybrid barriers.

The simple drapery system could be considered with passive as well as active functionality: it is applied on the detachment area, but it can rarely stabilize the shallow instability. In the proper sense, the simple drapery is aimed at slowing down the falling velocity of small blocks

or reducing the erosion process on debris slopes. The system may work properly if:

- the mesh lies as close as possible to the ground (slopes with regular morphology);
- the size of the falling material is relatively small (typically because of easily weathered lithotypes, or heavy jointed or thin layered rock masses);
- the mesh has enough weight to push the unstable blocks down and avoid their rolling/falling along gentle slopes (Figure 4).



Figure 4. Example of a simple drapery system with cable panels and double twist mesh. The weight of the mesh (approx. 5.0 kg/m^2) can avoid the rolling of single boulders (red arrows) along the slope.

However, if there are large falling masses or the slope morphology is uneven, the blocks can almost freely fall down. In that case, a "dynamic shield" is required, because the energy of the falling blocks becomes the most relevant effect. Dynamic shields are composed of strong and highly deformable meshes, able to dissipate the energy. They are usually installed on high rocky slopes (Figure 5), where the secured drapery systems are not cost-effective, or where the rockfall barriers and embankments cannot be installed due to the morphology of the site or difficult access.



Figure 5. Simple drapery system at Manic 2 (Québec, Canada). Average height of the slope approx. 40 m, surface approx. $5,000 \text{ m}^2$.

3 TYPE OF MESH

During the design, the first question that consultants must solve is: does the mesh perform a quasi-static or a dynamic behaviour?

The market offers a wide portfolio of meshes, such as single twist (chain link) or double twist wire meshes, steel geocomposites with cables and wires (SteelGrid), cable meshes, cable panels and ring net panels. The graph in Figure 6 recaps, in a semi quantitative way, the performances of the main meshes in the case of static and dynamic applications. The graph shows a non-direct proportion between the tensile resistance (quasi-static), and the dynamic resistance, which depends on the mesh deformability. For most applications, the dynamic resistance is useless and the required tensile resistance is pretty low. Other interventions require steel geocomposite (SteelGrid) to reduce the stresses on the suspension system. If high dynamic stresses are predicted (“dynamic shield”) High Energy Absorption (HEA) cable panels should be applied because of their high performance in dynamic conditions, such as for the attenuator systems (Arndt et al., 2009). If the dynamic impacts are extremely severe, rings nets are required.

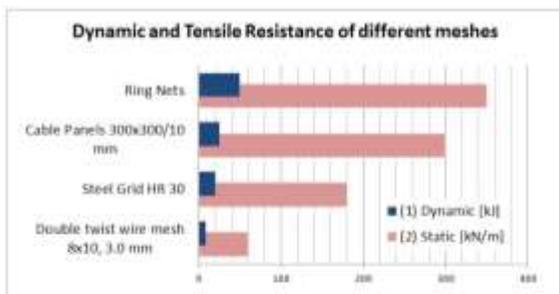


Figure 6. Comparison between the tensile (red pattern) and the dynamic (blue pattern) resistance of 4 different meshes (Grimod et al., 2013). The values are related to the most common mesh used per each family of nets. Notes: (1) Dynamic tests carried out on samples 2.0x2.5 m, completely restrained on 4 sides (Maccaferri internal report); (2) tensile resistance determined in accordance with the Italian standard UNI 11437:2012.

According to the literature (Muhunthan et al., 2005; Sasiharan et al. 2006), the inclusion of vertical ropes reduces the stress concentration on the mesh only if they are woven and not simply applied at the job site. The mesh coupled with interwoven cables is fit to transfer the loads directly to the top anchor system, thus the tension on the wires is reduced. Figure 7 describes the load effect on a simple drapery system in the case of a mesh without cables (Case A, top), and in the case of a mesh with woven edge cables (Case B, bottom). The figure defines 3 different load conditions on the system: theoretical case (left images), considering only the proper weight of the mesh (center images), and considering also the debris accumulation at the toe (right images). It is possible to define that in Case B the vertical cables minimize the typical deformation in the center of the roll, and they transfer the forces directly to the top anchor system. Therefore, the real condition (right image on the

bottom of Figure 7) looks like the theoretical one (left images on Figure 7). For this reason, SteelGrid, which is a woven composite mesh made of steel wire and metallic ropes woven together during the production of the hexagonal double twist wire mesh, is effective.

Figure 7 illustrates that SteelGrid mesh is ideal for use on high rock faces and slopes with a long drop or where large volumes of debris are expected. The inclusion of the longitudinal steel ropes enables the efficient transmission of loads to the crestline ropes and anchors, with minimal mesh deformation. This aspect allows the mesh to be stressed with larger loads or be maintained less, due to the increased capability of the system to contain debris at the toe.

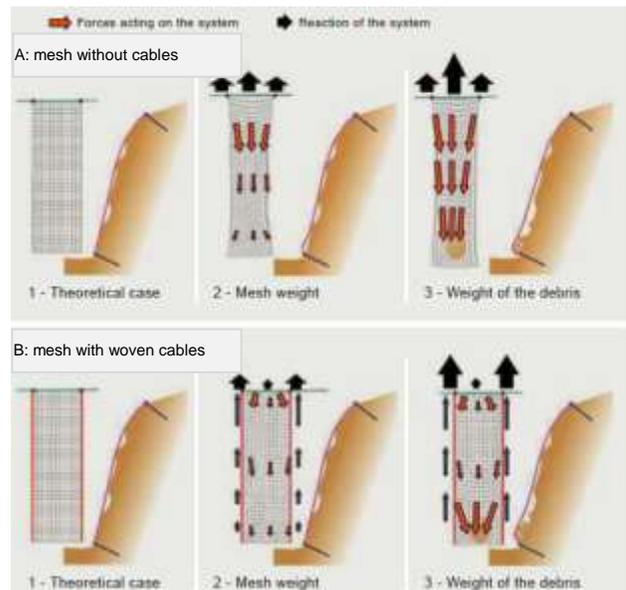


Figure 7. Comparison between a mesh without interwoven cables (Case A, top) and a mesh with interwoven cables: SteelGrid (Case B, below), considering 3 different load conditions.

Another important aspect to be evaluated during the mesh design is the capacity of the mesh to avoid unravelling. This is an intrinsic property of the mesh fabric. The mesh must be able to inhibit the propagation of the tears between the wires. In order to avoid this problem, double twist wire meshes are preferable to simple twists (i.e. chain link), which should be rejected. Research and laboratory tests show that damage to a double twist wire mesh remains local and the mesh does not unravel (Figure 8) (Agostini et al., 1988).

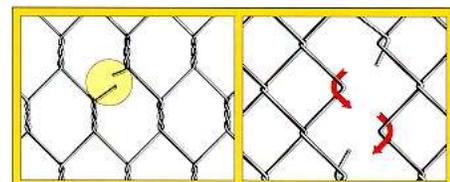


Figure 8. Comparison between a double twist mesh (left) and a single twist mesh (right) after a wire is cut. Double

twist mesh contains the propagation of the wire cut. Single twist mesh (i.e. chain link) unravels.

4 DESIGN OUTLINE

4.1 Factors affecting the design

The main factors affecting the proper choice of mesh for the simple drapery system are the following:

- a. Slope morphology: the probability of having dynamic impacts against the drapery increases if the slope is uneven and/or steep. For example, in the case of very uneven slopes, the drapery can only push on the crest lines and convexities, whereas the debris can freely run down in gullies and concavities. In this situation, drapery has a negligible capacity for erosion control, and the falling rocks can reach high velocities. Therefore, the installation of the drapery requires particular care in order to get contact between the ground and mesh, or the slope must be preventively regularized.
- b. Top anchor spacing: this factor is strictly related to the previous one, because the crest anchors must be placed in order to guarantee good mesh-ground contact. Moreover, the resistance of the crest supporting system must be increased if the space between the top anchors rises. In order to avoid over stress on the anchoring system (anchors and cable), the anchor spacing should be less than 3 or 4 m (max 5.0 m). When the anchor spacing is too large, several practical issues rise (design and field experiences show cases with cable spans up to 20 m). In this situation, cables with larger diameters must be used, though this can cause installation problems. In fact, ropes with diameters larger than 20-22 mm (3/4"-7/8") are really difficult to fix to the end termination of the lateral crest anchors. Moreover, if the cable span is too large, if a crest anchor accidentally fails, the suspension cable and the mesh are overstressed. Therefore, the system may be inefficient and maintenance costs increase.
- c. Prevalent instability: if erosion represents the main problem (typically on quite gentle debris slopes), the most suitable mesh should have a small opening size and enough weight to push down and stabilize the loose ground surface. As soon as the contact between the mesh and ground is achieved, the drapery becomes quite effective as erosion control. In fact, under this condition, it is possible to have growth of the vegetation (to obtain a better result the mesh can be coupled with an erosion control mat) and the retention of debris and boulders. If the slope is vertical, the drapery must be quite strong to absorb the impacts and guide rocks towards the bottom. In case of large blocks (i.e. in basalt cliffs), a "dynamic" drapery, like cable panels or ring nets, should be used. Whereas in case of small blocks (i.e. thin layered limestone cliffs), lighter draperies, like geocomposite SteelGrid or double twist wire mesh, might be sufficient.
- d. Expected life span of the drapery and maintenance costs. Regarding the life span, the design shall

consider the exposure of the mesh to aggressive environments (i.e. salted winds, water, etc.) and possible abrasion due to the debris movements. If the drapery is applied for temporary protection (i.e. mining industry) light corrosion protections (i.e. simple galvanisation with zinc) can be applied. On the other hands, heavier corrosion protections (i.e. alloy zinc-aluminum, stainless steel, polymeric coatings) may be required for permanent infrastructure applications. In term of maintenance, designers must forecast the maximum size of the debris pocket at the toe of the mesh or the dimension of the ditch at the base of the system. Once the designed accumulation limit is reached, the debris must be removed (from the mesh or from the ditch).

- e. Installation: rockfall mitigation solutions should be designed in order to minimize the exposure of workers to dangerous situations. Typically, if the mesh is too deformable (i.e. chain link mesh, or cable ring net, or cable mesh without any connections (i.e. knot or clip) between the ropes) the installation requires large efforts on site to join adjacent rolls of mesh due to the severe lateral contractions (as schematically shown in Figure 7, top-right). Experimental studies (i.e. Badger et al. 2009) show that the installation of cable panels (with strong connections between the cables) is almost 3 times faster than the one with cable ring nets, or other high deformable mesh (i.e. omega shape plot mesh).

4.2 Design goals

The main design goal of simple drapery systems is getting a proportioned protection system that gives the possibility for the components to work all together properly. Only the top anchor system could be slightly oversized in order to guarantee the safety of the foundations in case of the collapse of the lower part. Another goal is recognizing the limit load of the drapery system. This allows foreseeing the maximum height of the drapery, and when the cleaning of the debris pocket is required.

5 CALCULATION APPROACH

The design of simple drapery depends on different variables related to the geometry of the slope, the type of mesh and the hypothetical debris accumulation at the bottom of the system. Nowadays, the only research carried out to give a design guideline for these applications was done by the Washington State Department of Transportation (Muhunthan et al. 2005).

Using these studies, and the results obtained from several laboratory and field tests, Maccaferri has developed a new calculation approach (MacRo 2) which give the possibility to design the type of mesh, the up-slope longitudinal suspension cable and the characteristic of the crest anchors (diameter, type of steel and length). This tool allows designers to have a quick and easy, but reliable solution to the problem: often a complex numerical analysis has to be done, but this is not practical for every project, especially if the intervention

has a modest size and has to be done in a limited period of time (emergency protection).

The equations and the procedures at the base of this new formulation are quite simple and rough, but they give reliable and fast results considering the low accuracy level of input data.

5.1 Mesh design

The simple drapery system is a passive system capable of containing the debris at the bottom of the slope. It has to be designed by taking into account all the weights able to transmit a stress on the mesh:

1. The proper weight of the chosen mesh;
2. The weight of the debris accumulated at the toe of the mesh;
3. External weights, like snow or ice accumulation on the drapery.

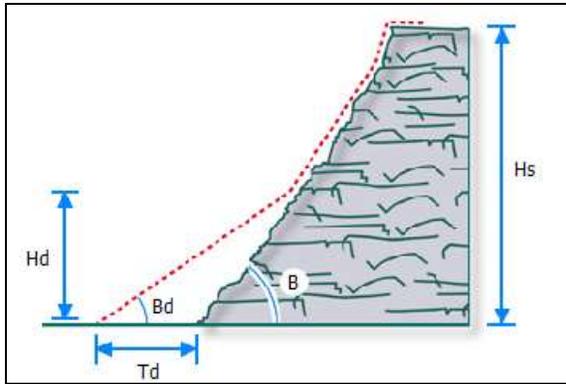


Figure 9. Geometrical input data used to calculate the stresses on the mesh due to the debris accumulation.

These three loads may be described by the following formulas, based on the research of the U.S. Department of Transportation FHA (Muhunthan et al. 2005).

First of all, the total load due to the mesh (W_m) has to be defined:

$$W_m = \gamma_m H_s / \sin\beta (\sin\beta - \cos\beta \tan\delta) \quad [1]$$

Where: γ_m = steel mesh unit weight; H_s = total height of the slope (figure 9); β = inclination of the slope (figure 9); δ = friction angle between mesh and slope, typical values are shown in Table 1.

Then, it is possible to identify the stress transmitted from the debris to the mesh (W_d) as follows:

$$W_d = \frac{1}{2} \gamma_d H_d^2 (1/\tan B_d - 1/\tan\beta)(\sin\beta - \cos\beta \tan\varphi_d) \quad [2]$$

Where: γ_d = debris unit weight; H_d = debris accumulation height (figure 9); φ_d = debris friction angle; B_d = debris external inclination value (Figure 9):

$$B_d = \arctan [H_d / (T_d + H_d / \tan\beta)] \quad [3]$$

Where: T_d = debris accumulation width (Figure 9).

Finally, the last load acting on the mesh is due to the snow or ice thickness above the mesh (W_s). It has be

noticed that for a slope with a grade (β) higher than 55 to 60 degrees, the load due to the snow should be neglected since the snow cannot be accumulated above this inclination (Swiss Guideline, 2007; Muhunthan et al. 2005).

$$W_s = \gamma_s t_s H_s / \sin\beta (\sin\beta - \cos\beta \tan\varphi_s) \quad [4]$$

Where: γ_s = snow (or ice) unit weight; t_s = snow (or ice) thickness, considered homogenous along the entire length of the mesh; φ_s = friction angle between soil and snow (or ice) (typical values are between 30° and 40°).

Table 1. Typical values of the mesh-ground friction angle (Sasiharan et al., 2006).

Characteristic of the slope	Value of the friction angle soil-mesh (δ)	Notes
Rough	$\geq 60^\circ$	The slope surface is very irregular and undulating and has many and/or prominent protrusion on the surface.
Undulating	36° to 59°	The slope is undulating but there are few and/or small abrupt protrusion on the surface.
Planar	25° to 35°	The slope is planar, and the surface is fairly smooth and has few undulations.

To design the drapery system at the limit equilibrium state, three partial coefficients have to be introduced in the calculation to increase the driving forces and decrease the resisting forces:

1. γ_{mts} = reduction partial coefficient, which reduces the tensile strength of the mesh (≥ 1.0 ; from the in-situ evidences and in-situ and laboratory tests, this factor should not be lower than 2.0).
2. γ_{vl} = load partial coefficient, which increases the variable loads, like the snow thickness and the debris accumulation (≥ 1.0 ; suggested value according to the Eurocode 7, 1997 = 1.5).
3. γ_{pl} = load partial coefficient, which increases the permanent loads, like the proper weight of the mesh (≥ 1.0 ; suggested value according to the Eurocode 7, 1997 = 1.3).

The acting and resisting forces at the limit equilibrium state can be calculated introducing the partial coefficients listed above. The total stress on the revetment (W_s) is:

$$W_s = (W_d + W_s) \gamma_{vl} + W_m \gamma_{pl} \quad [5]$$

The Serviceability tensile strength of the mesh (R_m) is calculated as:

$$R_m = T_m / \gamma_{mts} \quad [6]$$

Where: T_m = ultimate longitudinal tensile strength of the mesh (defined by laboratory tests, i.e. according to UNI 11437:2012, see Figure 6).

The design is satisfied if:

$$R_m - S_w \geq 0 \quad [7]$$

Thus, the safety factor of the mesh, which must be higher than 1, is equal to:

$$FS_{\text{MESH}} = R_m / S_w \geq 1 \quad [7.a]$$

5.1 Suspension cable design

The mesh is secured on the transversal up-slope suspension cable, which is fixed to the crest supports (anchors). Designers must know the maximum load acting on the drapery (defined in the previous paragraph: ΣW_i ; [1] [2] [4]) and the spacing between the up-slope anchors in order to calculate the deformation and the stress distribution within the rope. This method uses the principle of the catenary to verify if the tensile strength of the cable is sufficient to support the total weight of the system ($W_m + W_d + W_s$).

Thus, the cable is verified if the following equation is satisfied:

$$T_{\text{WLC}} - F_{\text{CABLE}} \geq 0 \quad [8]$$

Where: T_{WLC} = cable working load limit; F_{CABLE} = maximum tensile strength acting on the cable (calculated with the catenary solution).

$$T_{\text{WLC}} = T_{\text{CABLE}} / \gamma_{\text{CABLE}} \quad [9]$$

T_{CABLE} = ultimate tensile strength of the designed rope (it depends on the steel grade, the type of core and the diameter of the rope, i.e. see ASTM A1023/A 1023M, 2002 or UNI EN 12385-4:2008); γ_{CABLE} = safety coefficient decreasing T_{CABLE} (≥ 1.0).

The safety coefficient of the cable is then:

$$FS_{\text{CABLE}} = T_{\text{WLC}} / F_{\text{CABLE}} \geq 1 \quad [8.a]$$

Moreover, using the catenary it is possible to define the maximum length of the rope and its maximum sag between two consecutive anchors (Figure 10).

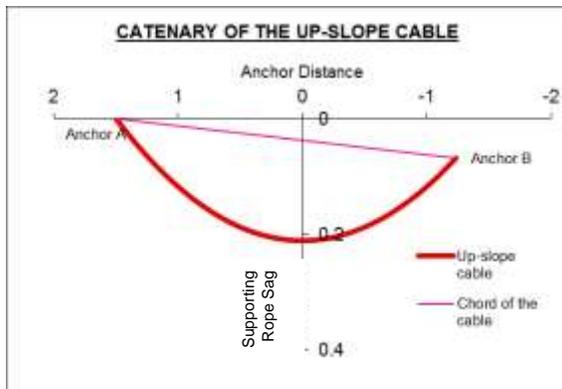


Figure 10. Example of the deformation of the up-slope cable (red line) between two anchors (A and B) calculated using the catenary.

5.2 Crest anchors design

The design of the crest anchors may be divided into two different steps. The first allows designing the anchor diameter and it takes into consideration the sheared load transmitted from the system, composed of the mesh and cable. The second is the definition of the minimum anchor length, which depends on the soil characteristics and the drilling diameter.

5.3 Evaluation of the anchor size

With the catenary theory it is possible to determinate the maximum force acting on the intermediate and lateral anchors. The forces on these two anchors differ because the supporting cable is considered as a catenary (Figure 11). The intermediate anchors would be less stressed because the load can be divided in two directions (to the right and left of the anchor). On the other hand, the lateral anchors would be more stressed because they must support all the load coming from the rope (the rope does not continue beyond the anchor).

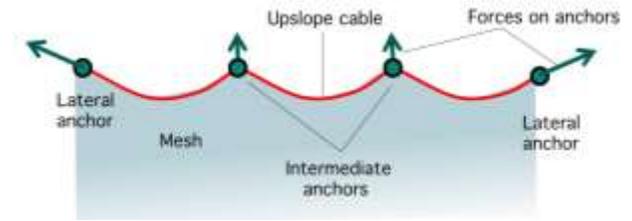


Figure 11. Distribution of the forces on the up-slope supporting cable and crest anchors. The cable is considered as a catenary.

Then, these two forces must be related to the working shear resistance of the designed anchors.

$$S_{\text{bar}(j)} - N_{(j)} \geq 1 \quad [10]$$

Where: $S_{\text{bar}(j)}$ is the working shear resistance of the anchor j ; $N_{(j)}$ = force that the cable and the mesh develop on the anchor j (calculated with the catenary solution); j = position of the anchor: intermediate or lateral.

$$S_{\text{bar}(j)} = (Y_{\text{bar}(j)} / \gamma_{\text{st}}) / 3^{1/2} \quad [11]$$

Where: $Y_{\text{bar}(j)}$ is the yield load of the steel bar j ; γ_{st} = safety coefficient for the steel strength of the bar (> 1.0).

$$Y_{\text{bar}(j)} = ESS_{(j)} \sigma_{\text{ADM}(j)} \quad [12]$$

Where: $ESS_{(j)}$ is the effective area of the steel bar j ; $\sigma_{\text{ADM}(j)}$ = yield stress of the steel of the bar j .

$$ESS_{(j)} = \pi / 4 \{ [\phi_{e(j)} - 2 t_{c(j)}]^2 - \phi_{i(j)}^2 \} \quad [13]$$

Where: $\phi_{e(j)}$ = external diameter of the steel bar j ; $t_{c(j)}$ = thickness of corrosion on the external crown of the steel bar j ; $\phi_{i(j)}$ = internal diameter of the steel bar j .

Thus, the safety coefficient of the different anchors may be calculated as follows:

$$FS_{ANCHOR(i)} = Sbar_{(i)} / N_{(i)} \geq 1 \quad [10.a]$$

5.4 Evaluation of the anchor length

The evaluation of the anchor (or nail) length takes into account the following:

- The nail plays an important role because it has to support the entire system. Its length must be deep enough to reach the stable rock.
- The steel bar and the grout are exposed to the superficial weathering influences (ice, rain, salinity, temperature variations, etc.).

The minimum theoretical length is derived by the equation:

$$L_{TOTAL(i)} = L_{S(i)} + L_p \quad [14]$$

Where: L_s = minimum foundation length (in the stable rock) calculate with the Bustamante-Doix formulation (Equation 15), L_p = safety length in order to increase the depth of the anchor (i.e. length of hole with plasticity phenomena: portion of the stable rock mass that loses its strength –plastification- due to the bend deformation of the anchor bar when it is stressed. Hence, this portion is not considered as a foundation for the anchors bars).

$$L_{S_j} = P_j / (\pi \phi_{drill} \tau_{lim} / \gamma_{gt}) \quad [15]$$

Where: ϕ_{drill} = diameter of the drill-hole (usually no lower than 40 mm); τ_{lim} = adherence tension between grout and rock (bond stress); γ_{gt} = safety coefficient of the adhesion grout – rock; P = pullout force (calculated with the catenary theory) for the internal and lateral anchors.

The length of the nail at this point has a preliminary value. The final suitable length of the bars has to be evaluated during the drilling in order to verify the exact nature of the soil and confirmed with pull out tests (Figure 12).



Figure 12. Example of a pull-out test to verify the designed length of the top anchors.

6 CASE STUDY: CARRIERE DEMIX (MONTREAL, QUEBEC)

A former quarry site in East Montréal is being converted into a biogas plant by the City of Montréal as part of its plan to reduce the carbon footprint of the City. During the period of 2006 – 2012, the City issued a series of tenders to design and install rockfall drapery mesh in the quarry in order to mitigate the potential of rockfall hazards to equipment and personnel that work at the base of the rock slopes, some of which exceed 120 m in height (Figure 13).



Figure 13. Front view of one of the rock slope at quarry Démix, before the installation of the rockfall mitigation system (average height of the cut approx. 120 m) (courtesy of CIMOTA Inc.).

Engineers with the City of Montréal designed the components of the rockfall drapery system. As the side walls of the quarry were very high and access very difficult due to the narrow, mid-face benches, the City wanted a drapery system that could be installed in one single piece that would drape the entire slope. No mid-face rock pinning would be done and a regular maintenance program that included cleaning up the rock debris was to be implemented.

The steel mesh geocomposite SteelGrid (Figure 14) was designed using the MacRo 2 design approach. This mesh was chosen due to the cost-effective advantages. The SteelGrid was designed with 8 mm cables on the lateral sides of a double twist wire roll 3.6 m wide (double twist type 8x10, 3.0 mm in diameter). To accommodate the height of the rock cut the mesh was manufactured in rolls 120 m long. In this way it was possible to decrease the installation time and avoid transversal connections between different rolls of mesh along the slope. In this way, the overall cost of the intervention was considerably reduced.



Figure 14. Detail of the cable woven in the double twist mesh to form the SteelGrid (in this example the cables are woven every 30 cm to reach very high performances).

The large 8 mm diameter wire ropes woven into the mesh helped to carry the self-weight of the larger rolls. According to research by the Washington State Department of Transportation, in cooperation with U.S. Department of Transportation (Muhunthan et al., 2005), the presence of these steel cables, woven within the mesh during the manufacturing process, enabled better stress distribution in the supporting cable and reduced the strain in the drapery system (Figure 7). The reduction of the stress on the mesh could increase the total load capacity of the mesh and consequently improve its life span and significantly reduce maintenance costs. Moreover, the hexagonal double twist mesh provided high resistance to the impacts of rocks and avoided unraveling in the event of wire breakage. Due to the limited life span of the mesh, wires and cables of the geocomposite were coated with a heavy zinc-galvanisation.

The solution was selected considering other two main aspects: low maintenance of the system and no reduction on the road width at the base of the rock cuts. More than 40,000 m² of Simple Drapery System were installed in 2 different portions of the quarry in 2012 by CIMOTA Inc. The upper longitudinal cable and the crest anchoring systems were designed according to the calculation principle illustrated in this paper. To hold the mesh at the top of the slope, a 16 mm cable was installed between the crest cable-anchors (16 mm in diameter, 3.0 m long, and spaced every 3.0 m) (Figure 15).



Figure 15. Detail of the installation of the mesh around the suspension cable at the top of the rock cut (courtesy of CIMOTA Inc.).

A view of the completed installation is shown in Figure 16.



Figure 16. General front view of the rock slope where more than 40,000 m² of SteelGrid were installed in 2012 (courtesy of CIMOTA Inc.).

6.1 Design of the mesh using the MacRo 2 approach

Hereafter are summarized the steps of the simple drapery system design.

The input data used during the calculation are listed below in Figures 17 to 20:

Rock Slope

Slope inclination [°]	B	80
Slope total height [m]	Hs	120.00
Debris accumulation height [m]	Hd	0.30
Debris accumulation width [m]	Td	0.30
Debris accumulation angle [°]	Bd	49.87
Debris friction angle [°]		20.00
Debris unit weight [kN/m ³]		20.00
Friction angle between mesh and slope [°]		25.00

Snow

Snow unit weight [kN/m ³]		8
Snow thickness [m]		0.01

Figure 17. Input data related to the geometry and intrinsic parameter of the slope and the rock. The extra load (snow) has been considered as a 1 cm homogeneous thickness of ice acting along the entire mesh.

Mesh

Mesh type	Steelgrid MO 300	
Tensile resistance [kN/m]		60.00
Steel mesh unit weight [Kg/m ²]		1.78

Figure 18. The chosen mesh is a SteelGrid (type MO 300), characterized by a nominal tensile resistance of 60 kN/m (test according to UNI 11437:2012) and a unit weight of 1.78 kg/m².

Crest Rope + Crest Anchorages

Layout of crest rope installation	
Horizontal anchor spacing [m]	3.00
Vertical offset between crest anchors [m]	0.00
Crest Rope Specification	
Rope diameter [mm]	16
Rope steel grade [MPa]	1770
Rope core type	Steel
Rope ultimate tensile strength [kN]	183.2
Crest Anchor Specification	
Anchor type	Rope cable anchor - single leg
Anchor internal diameter (where hollow) [mm]	0
Anchor external diameter [mm]	16
Thickness of corrosion crown [mm]	0
Anchor yield stress (of steel) [MPa]	1770
Rock-grout adhesion (bond stress) [MPa]	0.70

Figure 19. The supporting system is composed by flexible 16 mm rope anchors, spaced 3.0 m, and a 16 mm up-slope cable (type 6x19+IWRC – 1770 MPa, in accordance with ASTM A1023/A 1023M, 2002).

Safety Coefficients

Rock Slope	
Safety coefficient for variable loads (snow or debris)	1.50
Safety coefficient for permanent loads	1.30
Mesh	
Safety reduction for mesh resistance	2.00
Geometry of the top longitudinal cable	
Safety reduction on X spacing	1.00
Safety reduction on Y vertical gradient	1.00
Cable type	
Safety reduction for cable resistance	2.00
Anchor type	
Coefficient for the steel bar yield stress	2.50
Coefficient for rock-grout adhesion (bound stress)	2.50

Figure 20. Load and reduction partial safety coefficients. Load coefficients, which increase the forces acting on the system, are related to the rock slope (variable and permanent loads). The other coefficients (related to the mesh, geometry, cable, anchor) reduce the resistance of the components of the system.

As per output, they have been defined by the safety factors (≥ 1.0) of all the components of the system and the minimum length of the crest flexible rope anchors. Table 2 summarizes the results obtained with MacRo 2:

Table 2. Output from MacRo 2 calculation.

Element	Factor of safety or value
Mesh Capacity:	FoS = 1.83 \geq 1.0 - Satisfied
Supporting up-slope cable:	FoS = 1.47 \geq 1.0 - Satisfied
Intermediate crest anchors:	FoS = 2.42 \geq 1.0 - Satisfied
Lateral crest anchors:	FoS = 1.32 \geq 1.0 - Satisfied
Min. length of the crest anchors:	$L_{\min} = 2.3 \text{ m}$ ($\phi_{\text{drill}} = 40\text{mm}$) (adopted: $L = 3.0 \text{ m}$)

7 CONCLUSION

A simple drapery system is a cost effective remedial measure against the rockfall hazards: it is successfully used in several domains (i.e. mining industry, highway and railway protections), and in severe application conditions (i.e. slope height up to 100-150 m) and it is quick and easy to install.

The effect of this kind of intervention is to control the falls of rocks and debris, which are driven toward the bottom with slow velocity and reduced energy. In comparison to other types of rockfall interventions, they are simpler, faster and cheaper to install, and their maintenance is generally easier and does not require skilled crews. Nevertheless, they cannot be considered as a remediation for shallow instabilities.

Based on research carried out by Muhunthan et al. 2005 and in-situ and laboratory tests, Maccaferri has developed a calculation approach (MacRo 2) able to optimize all the basic components of the drapery system (mesh, supporting cable and crest anchors), and evaluate the required maintenance. Moreover, the new concept of steel geocomposite is introduced to optimize the mesh to be used for simple drapery mesh application and reduce the stresses on the system.

Further research is needed for a better estimation of the dynamic behavior of the draperies.

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