Design of Simple Drapery Systems 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 the highways and railways. It is generally used for rock cuts or natural rock faces. The system is a fast and cost-effective rockfall hazards mitigation measure, 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 to define all the components of the system. A case study of a drapery system recently designed and installed in Indonesia is presented.
Keywords: rockfall, remediation, metallic mesh, drapery, Indonesia

1. INTRODUCTION

The natural process of weathering generates geological instabilities which frequently expose mining areas, and infrastructures to a wide range of shallow instabilities, which may vary from erosion to rock falls. Despite they mostly cause small size falling, the shallow instabilities cannot be underestimated because they use to 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. In spite of the technical literature furnishes many precious information 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 typologies. In this sense the designer 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 to install 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 for their entire length. The supports ae considered passive, because they do not require any pre-tensioning, and they start to work only if they are stressed by the loads acting on the mesh (they shall not be considered bolts or tie-back anchors). 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.

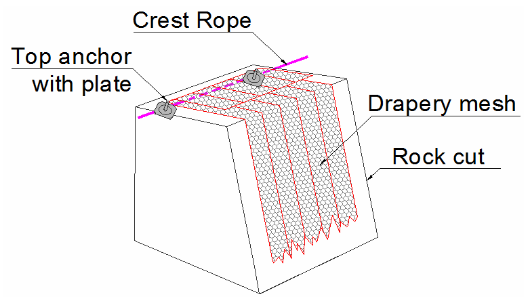

Figure 1. Sketch of a simple drapery system application

Subsequently, the drapery 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

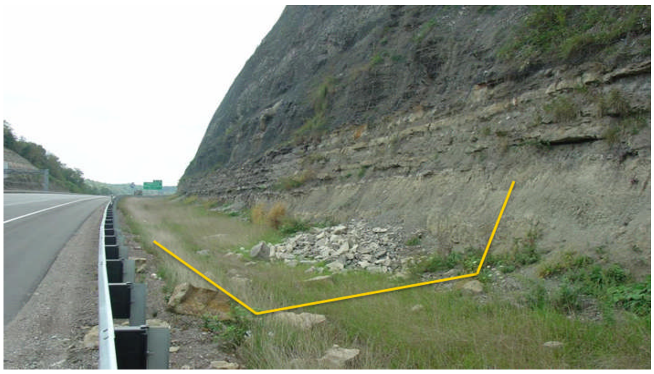

Figure 3. Example of a simple drapery mesh with a ditch (highlighted with the yellow line) at the base to collect the debris falling from the slope

In comparison to other types of rockfall interventions (i.e. secured drapery systems, rockfall barriers, etc.), the simple drapery is more cost-effective, and its maintenance is easier, but on the other hand it cannot be considered the remedy for shallow instabilities, because it can only mitigate the effect of the falling trajectories. This system is usually installed on high rocky slopes, where pin drapery systems are not too costly, or where rockfall fences or rockfall embankments cannot be installed due to the uneven or high gradient of the slope.

Figure 4. Simple drapery system for temple protection (India).

3. TYPE OF MESH

During the design, the first question that consultants must solve is "Does the mesh have 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 5 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.

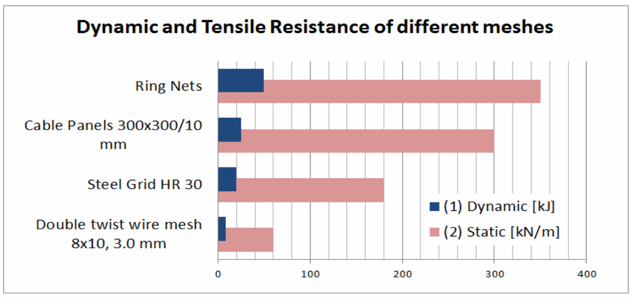

Figure 5. Comparison between the tensile (red pattern) and the dynamic (blue pattern) resistance of 4 different meshes (Grimod et al., 2013). The values are related to the most common mesh used per each family of nets. Notes: (1) Dynamic tests carried out on samples 2.0x2.5 m, completely restrained on 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. The figure below describes the load effect on a simple drapery system in the case of a mesh without cables (cases A, above), and in the case of a mesh with woven edge cables (cases B, below).

The figure defines 3 different load conditions on the system: theoretical case (left images), considering only the weight of the mesh (center images), and considering also the debris accumulation at the toe (right images). It is possible to observe that in case B the presence of the vertical cables minimizes the deformation in the center of the panel, and the ropes transfer directly the forces to the top anchor system. Therefore, the real condition (bottom-right image in figure 6) looks like the theoretical one (left images on figure 6). 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 6 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 longitudinal steel ropes enable 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 less maintained, thanks to the increased capability of the system to retain debris at the toe.

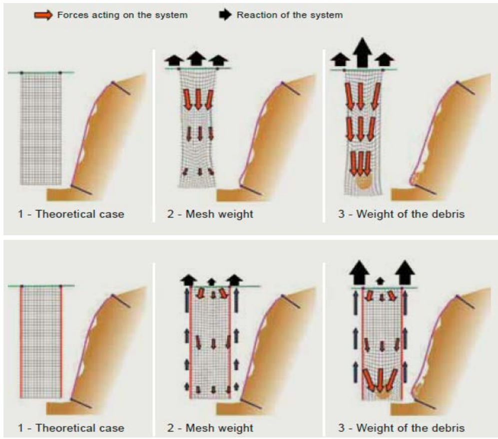

Figure 6. Comparison between a mesh without interwoven cables (case A, above) and with interwoven cables: SteelGrid (case B below), considering 3 different load conditions

Another important aspect to be evaluated during the mesh design is the capacity of the mesh to avoid the 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 issue, double twist wire meshes are usually preferred to simple twist meshes (i.e. chain link). Researches and laboratory tests show that damage to a double twist wire mesh remains localized and the mesh does not unravel (figure 7) (Agostini et al., 1988).

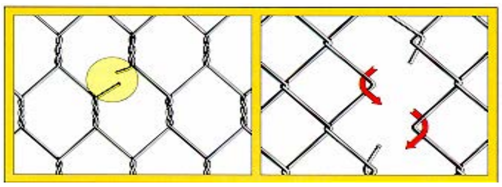

Figure 7. Comparison between a double twist mesh (left) and a single twist mesh (right) after a wire is cut. Double twist mesh contains the propagation of the wire cut. Single twist mesh (i.e. chain link) unravels.

4. DESIGN

4.1 Factors influencing the design

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

1. Slope morphology: the probability to have dynamic impacts against the drapery increases if the slope is uneven and/or steep. For instance, in case of very uneven slopes, the drapery can only push on the crest lines and convexities, whereas the debris can freely run down on gullies and concavities. In this situation drapery has a negligible capacity in erosion control, and the falling stones can reach high velocities. Therefore, the installation of the drapery requires a particular care in order to maximise the contact between ground and mesh, or the slope must be preventively regularized.
2. Top anchor spacing: this factor is strictly related to the previous one, in fact the crest anchors shall be placed in order to guarantee a good contact mesh-ground. Moreover, the resistance of the crest supporting system must be increased if the space between the top anchors rises. In order to generate over stress on the anchoring system (anchors and cable), the anchor spacing should be generally lower than 3 - 4 m.
3. Prevalent instability: if the erosion represents the main problem, the most suitable mesh should have small opening size and enough weight to push down and stabilize the loose ground surface. As soon as the contact between mesh and ground is reached, the drapery becomes quite effective as erosion control. In fact, under this condition, it is possible to have the 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 the debris towards the bottom. In case of large blocks, a “dynamic” drapery, like cable panels or ring nets, should be foreseen. Whereas in case of small blocks (i.e. thin layered limestone cliff) lighter draperies, like geocomposite SteelGrid or double twist wire mesh, might be sufficient.
4. 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 the 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. Whereas, heavier corrosion protections (i.e. zinc-aluminum alloys, polymeric coatings) may be required for permanent infrastructures applications. In term of maintenance, designers shall predict 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 shall be removed (from the mesh pocket or from the trench).
5. Weight: the weight affects the capacity of the system to stabilize single boulders. If the mesh is too light, its capacity to push down and stabilize large blocks is reduced. Heavy meshes (i.e. cable panels) may avoid the rolling/falling of block along gentle slopes (figure 8).

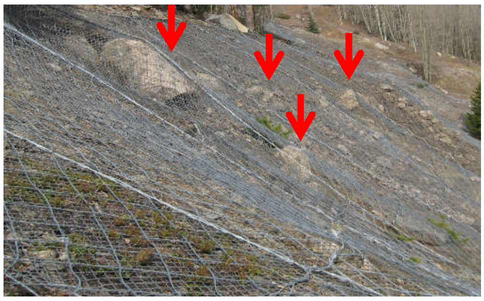

Figure 8. Example of a simple drapery system with cable panels and double twist mesh. The proper weight of the meshes (approx. 5.0 kg/m2) can avoid the rolling of single boulders (red arrows) along the slope.

4.2 Design goals

The main design goal of simple drapery systems is getting a proportioned protection system that gives the possibility to the single 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 to predict 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 laboratories and field tests, Maccaferri has developed a new calculation approach (implemented in the software 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 designer to have a quick and easy, yet reliable solution to the problem. Sometimes, a complex numerical analysis has to be done, but this is not practical for all projects, 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 design approach are quite simple, but they give reliable and fast results.

5.1 Mesh design

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

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

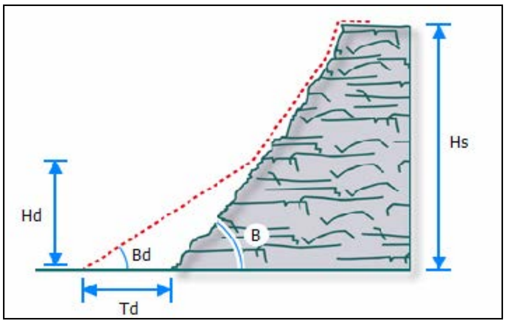

Figure 9. Geometrical input data used to calculate the stresses on the mesh due to the debris accumulation

These three loads may be described by the following formulas, based on the researched of the U.S. Department of Transportation FHA (Muhunthan et al. 2005).
Firstly, the total load due to the mesh (Wm) has to be defined:

$$Wm = \gamma_m Hs / \sin\beta (\sin\beta - \cos\beta \tan\delta) \quad (1)$$

Where:
γm = steel mesh unit weight;
Hs = 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.

Table 1. Typical Values of The Friction Angle Mesh-ground (Sasiharan et al., 2006).

Characteristic of the slope	Value of the friction angle soil-mesh (δ)	Notes
Rough	≥ 60°	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.

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

$$Wd = \frac{1}{2} \gamma d\ Hd^2 \left(\frac{1}{\tan Bd} - \frac{1}{\tan\beta} \right) (\sin\beta - \cos\beta \tan\varphi_d) \quad (2)$$

Where:
γd = debris unit weight;
Hd = debris accumulation height (figure 9);
φd = debris friction angle;
Bd = debris external inclination value (figure 9):

$$Bd = \arctan[Hd / (Td + Hd / \tan\beta)] \quad (3)$$

Where, *Td* is debris accumulation width (figure 9).

Finally, the load acting on the mesh due to snow or ice presence shall be calculated (Ws). It is important to notice that that for slopes with an inclination on the horizontal (β) higher than 55-60 degrees the load due to the snow could be neglected since the snow cannot be accumulated on such a steep slope (Swiss Guideline, 2007; Muhunthan et al. 2005).

$$Ws = \gamma s\ ts\ Hs / \sin\beta (\sin\beta - \cos\beta \tan\varphi s) \quad (4)$$

Where:
γs = snow (or ice) unit weight;
Ts = snow (or ice) thickness, considered homogenous along the entire area to be protected;
φs = friction angle between soil and snow (or ice) (typical values are between 30° and 40°).

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

1. γmts = 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. γvl = 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. γpl = load partial coefficient which increases the permanent loads, like the weight of the mesh (≥ 1.0; suggested value according to the Eurocode 7, 1997 = 1.3).

The total stress acting on the netting (Sw) is therefore:

$$Sw = (Wd + Ws)\gamma vl + Wm\ \gamma pl \quad (5)$$

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

$$Rm = Tm / \gamma mts \quad (6)$$

Where, *Tm* is ultimate longitudinal tensile strength of the mesh (defined by laboratory tests, i.e. according to UNI 11437:2012 or BS EN 10223-3:2013, see figure 4).
The design condition is satisfied if:

$$Rm - Sw \geq 0 \quad (7)$$

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

$$FS_{MESH} = Rm / Sw \geq 1 \quad (7.a)$$

5.2 Crest cable design

The mesh is secured to the transversal up-slope suspension cable, which is fixed to the crest supports (anchors). Designer shall calculate the maximum load acting on the drapery (defined in the previous paragraph: ΣWi (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 utilizes the principle of the catenary to verify if the tensile strength of the cable is sufficient to support the total weight of the system (Wm + Wd + Ws).

Thus, the cable check is passed if the following equation is satisfied:

$$T_{WLC} - F_{CABLE} \geq 0 \quad (8)$$

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

$$T_{WLC} = T_{CABLE} / \gamma_{CABLE} \quad (9)$$

Where T_{CABLE} is ultimate tensile strength of the designed rope (it depends on the steel grade, the type of rope core and the diameter of the rope, i.e. see ASTM A1023/A 1023M, 2002 or UNI EN 12385-4:2008), and γ_{CABLE} is safety coefficient which reduces T_{CABLE} ($\geq$ 1.0).
The safety coefficient of the cable is therefore:

$$FS_{CABLE} = T_{WLC} / F_{CABLE} \geq 1 \quad (8.a)$$

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

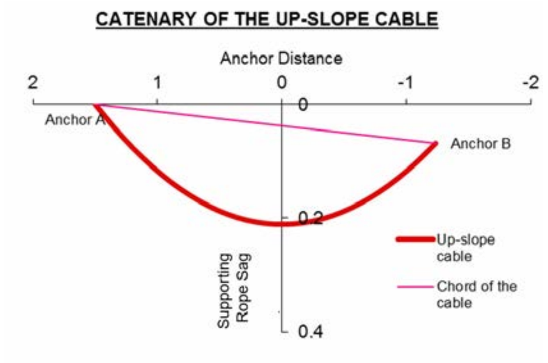

Figure 10. Example of the deformation of the up-slope cable (red line) between two anchors (A and B) calculated using the catenary model.

5.3 Crest anchors design

The design of the crest anchors can be divided in 2 different steps. The first step allows to design the anchor diameter and it takes into consideration the shear stresses transmitted by the drapery system. The second step allows to define the minimum anchor length, which is a function of the soil characteristics and the drilling diameter.

5.4 Anchor size

With the catenary theory it is possible to determine 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 are less stressed because the load can be divided in 2 directions (acting to the right and to the left of the anchor). Instead, the lateral anchors are more stressed because they must support the entire load transmitted by the rope.

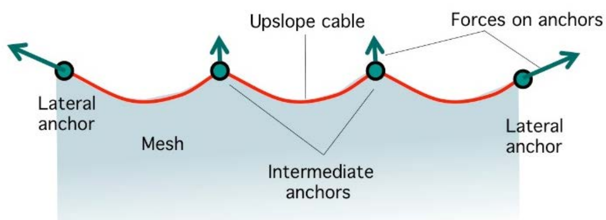

Figure 11. Distribution of the forces on the up-slope supporting cable and crest anchors. The cable is considered as a catenary.

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

$$Sbar(j) - N(j) \geq 1 \quad (10)$$

Where, Sbar(j) is the working shear resistance of the anchor j, N(j) is force that the cable and the mesh transfer to the anchor j (calculated with the catenary solution), and j is position of the anchor (intermediate or lateral).

$$Sbar(j) = (Ybar(j) / \gamma st) / 3^{1/2} \quad (11)$$

Where, Ybar(j) is the yield load of the steel bar j, and γst is safety coefficient for the steel strength of the bar (> 1.0).

$$Ybar(j) = ESS(j)\, \sigma_{ADM}(j) \quad (12)$$

Where, ESS(j) is the effective area of the steel bar j, and $\sigma_{ADM}(j)$ is yield stress of the steel of the bar j.

$$ESS(j) = \pi / 4 \left\{ \left[\phi e(j) - 2tc(j) \right]^2 - \phi i(j)^2 \right\} \quad (13)$$

Where:
ϕe(j) = external diameter of the steel bar j;
tc(j) = thickness of corrosion on the external crown of the steel bar j;
ϕi(j) = internal diameter of the steel bar j.
Thus, the safety coefficient of the different anchors may be calculated as follows:

$$FS_{ANCHOR(j)} = Sbar(j) / N(j) \geq 1 \quad (10.a)$$

5.5 Anchor length

The evaluation of the anchor length shall take into account the following:

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

The minimum theoretical length is derived with the following equation:

$$L_{TOTAL(j)} = Ls(j) + Lp \quad (14)$$

Where, Ls is minimum foundation length (in the stable rock) calculate with the Bustamante-Doix formulation (equation 15), Lp is 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 –plasticisation- 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).

$$Lsj = Pj / (\pi\, \phi drill\, \tau \lim / \gamma gt) \quad (15)$$

Where:
ϕdrill = diameter of the drill-hole (usually no lower than 40 mm);
τlim = adherence tension between grout and rock (bond stress);
γgt = 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 determined at this point is a preliminary value. The final suitable length of the bars shall be confirmed after in-situ 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: MAROS ELEVATED ROAD

The construction of a new road corridor in Maros needed some massive cutting of the existing rock slopes to gain room for the elevated road (Figure 13). During the period of 2017 – 2018, the local Public Works department issued a tender to design and install rockfall drapery mesh along the exposed cut slopes in order to mitigate the potential of rockfall hazards to vehicles and people the base of the slopes, some of which exceed 30 m in height.

Figure 13. View of the rock slopes during cutting operations for the new Maros elevated road.

Engineers, together with the local Public Works technical department based in Makassar, designed the components of the rockfall drapery system. The client wanted a drapery system that could be installed in one single piece that would drape the entire slope. A drapery system with steel meshes was selected for clear cost-effective advantages compared to other traditional solutions such as shotcrete. The contractor in charge of the execution selected the SteelGrid as netting material. The material selected such as netting, anchors, grouting, ropes, and accessories were in compliance with the recently developed national specification for Public Works rockfall protection projects (Spesifikasi Khusus Interim SKh. 1.3.16: Jaring Kawat dan Jaring Kabel Sebagia Pengaman Lereng Batuan).

Figure 14 illustrates the typical cross section of the rockfall protection system. The system was divided in two different types of intervention: an active system for the upper part of the slope (Zona A) and a passive system for the lower portion of the slope (Zona B). The protection system applied to Zona A and Zona differs by the fact that in Zona A, the rockfall netting is secured to the rock slope by means of rock anchors.

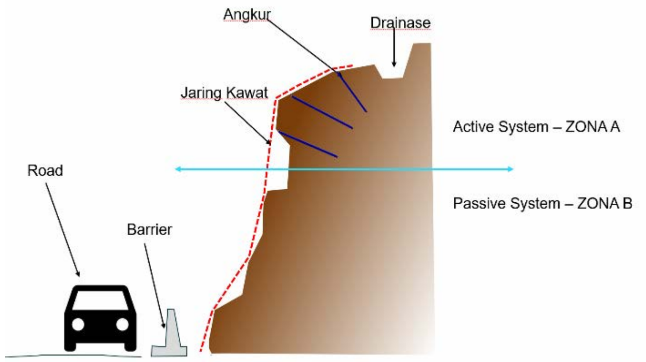

Figure 14. Sketch representing the slope cross section and the type of rockfall protection to be implemented.

To accommodate the height of the rock cut the mesh was manufactured in customized rolls with variable length (from 15m to 50m) long. In this way it was possible to decrease the installation time and minimize transversal connections between rolls of mesh along the slope. In this way, the overall cost of the intervention was considerably reduced.

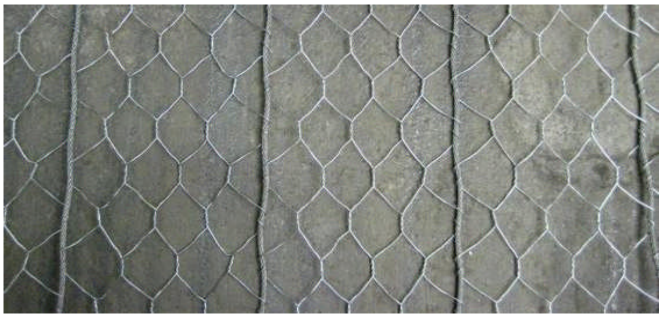

Figure 15. Detail of the cable woven in the double twist mesh to form the SteelGrid (the 8mm cables are interwoven in the mesh with 30 cm spacing in order to reach very high tensile resistance, up to 177 kN/m).

According to the research done in 2005 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 6). The reduction of the stress on the mesh could increase the total load capacity of the mesh and consequently improving the life time and significantly reducing the maintenance costs. Moreover, the hexagonal double twist mesh provided high resistance to the impacts of rocks avoiding the unraveling in the event of wire breakage. In order to comply with the durability requirements of the client, wires and cables of the geocomposite were coated with class A Zinc95%-Aluminum5% alloy (according to EN 10244-2).

According to the calculation principle illustrated in the paper, the upper longitudinal cable and the crest anchoring systems have been designed. To hold the mesh at the top of the slope a high tensile strength 22 mm cable was installed between the crest cable-anchors (32 mm in diameter, 4.0 m long, and disposed every 3.0 m). The selected anchors were type BJTS 50.

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

The input data used during the calculation are listed below:

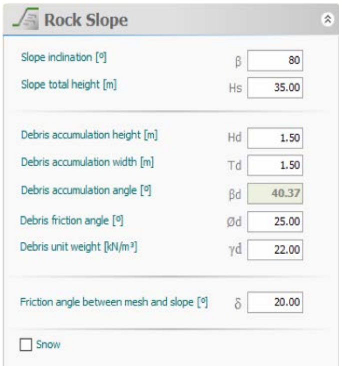

Figure 16. Input data related to the geometry.

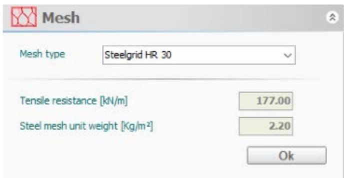

Figure 17. The chosen mesh is a SteelGrid (type HR 30), characterized by a nominal tensile resistance of 177 kN/m (test according to EN 10223-3:2013) and a unit weight of 2.2 kg/m2.

Crest Rope + Crest Anchorages

Layout of crest rope installation	
Horizontal anchor spacing [m]	3.00
Vertical offset between crest anchors [m]	0.20
Crest Rope Specification	
Rope diameter [mm]	**22**
Rope steel grade [MPa]	1770
Rope core type	Steel
Rope ultimate tensile strength [kN]	305
Crest Anchor Specification	
Anchor type	**BJTD 50**
Anchor internal diameter (where hollow) [mm]	0
Anchor external diameter [mm]	32
Thickness of corrosion crown [mm]	0
Anchor yield stress (of steel) [MPa]	500
Rock-grout adhesion (bond stress) [MPa]	0.50

Figure 18. The supporting system is composed by 32 mm steel bar anchors, spaced 3.0 m, and a 22 mm up-slope cable (type 6x19+IWRC – 1770 MPa).

The table below summarize the safety factors of all the system components obtained with MacRo 2:

Table 2. Output from MacRo 2 calculation.

Element	Factor of safety or value
Mesh Capacity:	FoS = 2.8 ≥ 1.0 - Satisfied
Supporting up-slope cable:	FoS = 1.09 ≥ 1.0 - Satisfied
Intermediate crest anchors:	FoS = 3.25 ≥ 1.0 - Satisfied
Lateral crest anchors:	FoS = 1.39 ≥ 1.0 - Satisfied
Min. length of the crest anchors:	L_{min} = 4.74 m (ϕ_{drill}=40mm) (adopted: L=5.0 m,(ϕ_{drill} = 76mm)

Figure 19. Installation of rockfall netting for Maros elevated road.

The design assumptions regarding the rock-grout adhesion (bond stress) were verified with in-situ pull-out tests.

Figure 20. The rock-grout

7. CONCLUSIONS

A simple drapery system is a cost-effective measure to mitigate rockfall hazards. This system has been successfully and extensively used in several scenarios (e.g. mining, highway and railway protections), and in complex conditions (slope height up to 150 m). The aim of this kind of intervention is to control the falls of the unstable rocks and debris, which are driven toward the bottom with reduced velocity and therefore reduced energy. In comparison to other types of rockfall interventions such as secured drapery systems or rock anchors, they are simpler to install, and their maintenance is easier.

Nevertheless, they cannot be considered as a remediation measure for shallow instabilities. Based on the researches carried out by Muhunthan et al. 2005 and in-situ and laboratory tests, Maccaferri has developed a calculation approach (implemented in the software MacRo 2) able to optimize all the components of a drapery system (mesh, supporting cable and crest anchors), and estimate the required maintenance. Moreover, the case of the simple drapery system installed for the protection of the new Maros elevated road in South Sulawesi (Indonesia) has been presented. References

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