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Selection of membranes and linking method in slope stabilization systems for the reduction on the installation time using multi-criteria decision analysis

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ABSTRACT

Flexible systems anchored to the ground are low visual impact alternatives to be used in slope protection. With the aim of reducing their installation time and costs the mechanical union between layers of membranes is proposed to be done in warehouses instead of independent installations on site. The most appropriate component selection and linking method is selected using multi-criteria decision analysis, specifically using AHP, WASPAS and TOPSIS techniques. The criteria considered in order to take the decision are cost of materials, ease of sewing, transport and installation of the system, biodegradability of the secondary mat and its hydroseeding retention capacity that stimulates the revegetation. Due to the uncertainty on the data of biodegradability, four scenarios were analysed. The results indicate that the most suitable secondary membrane in all cases is the coconut fibre mesh and should be connected to the main membrane using a cable tie machine.

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1. Introduction

Anchored flexible membranes are systems used in a slope with the aim of minimizing damages caused in roads, towns or railways due to a rockfalls, surface erosion or landslides [1–4]. They cover the slope surface with wire meshes or cable nets (which we will call main membranes), fixing them with anchorages and bolts stopping in that way the instability.

Generally, two types of anchored flexible membranes exist that depend on the level of resistance. Low resistance systems are mainly focused on guiding the small rock fragments or landslide from the detaching area to the road ditch. Hence, they are not aimed at holding the rockfall or preventing the detachment but avoiding their invasion of the road. In these systems triple torsion wire meshes are used, fixed in the upper line of the slope and at the sides of the stabilization area [5,6]. Triple torsion wire meshes [7], besides having a lower resistance than cable nets or high resistance wire meshes, have a higher deformation capacity, so they are not suitable for rockfall prevention, but they are ideal for these purposes. On the other side, high resistance systems, the ones on which this paper is focused, do have a stabilization aim, and in case of a slide, they retain the loose material and hold it close to the detaching area instead of letting it displace to the slope base. High resistance systems are composed of a main membrane and a secondary membrane extended over the slope, with reinforcement cables generally forming a square grid that transmits the load to the ground by means of the anchorages using bolts with a fixing plate. There are two typologies of main membranes: cable nets or wire meshes [8]. Cable nets are manufactured with galvanized steel braided cable between 8 and 10 mm generating a squared pattern with sides between 200 mm and 300 mm. Intersections of cables are fixed using clips created ad hoc or wire. Its resistance will depend on the reticule size, shear strength of the clips, ultimate strength of the steel or material of the core (could be made of steel or could have a textile core). Wire meshes of simple torsion are manufactured in medium resistance (600–800 N/mm2) or high resistance (up to 1700 N/mm2) steel wire. They form squares or

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rhombus of variable dimensions and wire sections depending on the product, but generally between 3 and 6 mm. Concerning the secondary membranes, they are generally used to retain the soil or rocks covering the gaps left by the main membrane, and promote the growth of vegetation. Three different types of membranes could be used for this aim. Triple torsion wire meshes are installed specially when dealing with rock slopes. In soil slopes, however, geogrids made for soil reinforcement or erosion control mats, either plastic or organic, are widely used.

The installation of these high resistance systems consists of 6 steps illustrated in Fig. 1 [8]. The first one is the extension of the membrane or membranes. The installation of the membranes is executed from the more internal to the more external, one at the time. Secondly, the reinforced cables are disposed, generally forming squares or rhomboids. After that, in the intersection points, where the anchorage must be located, the workers proceed with the anchorage drilling and anchorage injection. The fifth step is the pre-stress of the system applying a stress from the ends of the reinforced cables. At last, in soil slopes revegetation is a common practice (see Figs. 2–4)

To avoid the duplicity of the installation activities of two membranes (corresponding to Step 1) and to reduce the installation costs, the solution found was the design of an integrated material. So, by finding a way to connect the main (cable net or wire mesh) and secondary membranes (geomat, geogrid, biomat, etc.) at the inside of the warehouse, the installation is reduced to the setting over all the slope to be protected of only one membrane (made of the two main and secondary membranes) instead of dealing with the two ones separately and independently, which doubles the installation time. Since the options to be considered to obtain a reduced time flexible membrane configuration are multiple, multi-criteria decision analysis (MCDA) was found to be a suitable tool to fulfill this aim.

MCDA has already been employed successfully with civil engineering purposes like the improvement of pavements or sustainable urban drainage systems (SUDS). Authors like Torres-Machi et al. 2019 [9] used these methods to evaluate the sustainability of different pavement alternatives, and others like Elizondo-Martinez et al. 2020 [10] took advantage of MDMA to find out the additives and fibers to reach a more resistant porous concrete pavement. Wang et al. 2017 [11] were able to select the best drainage design using seven different criteria and twelve indicators. A more extended view of the MCDA techniques and their uses in construction/civil engineering are explained in Jato-Espino et al 2014 [12]. Focusing on slope stabilization, Talema et al. 2017 [13] were able to find out the most suitable plant species for the stabilization of a riverbank. Besides, Wu et al. 2017 [14] used a multi-criteria analysis to select the best solution of slope stabilization in a specific site, obtaining the compacted soil–cement as the first option considering safety assurance, time, sustainability workability or economy. Only one paper was found to use MCDA in the systems whose focus of attention are flexible membranes, dealing in this specific case with the selection of the most suitable wire rope (cable) type for the system [15].

2. Individual components and linking methods

2.1. Main membranes

For the main membrane, the more commonly used are the square cable nets and the high resistance wire meshes (like TECCO® or MT15000). Two reticule sizes of the square cable net were used in this study with the same cable diameter of 8 mm, the first one with a square side of 200 mm and the second one of 300 mm. In the case of the wire mesh, TECCO® shape was used (with a rhomboidal reticule size of 83x143 mm) with two strand diameters: TECCO® 65/3 with a diameter of 3 mm and TECCO® 65/4 with a diameter of 4 mm.

2.2. Secondary membranes

This research is mainly focused on stabilization systems to be installed in soil slopes. That is why geomats, organic mats or erosion control mats should be used under the main membranes explained in the section above. Five membranes were found to be suitable for this aim. The first one, FORTRAC, is a geogrid with a square and plain reticle pattern. The second geogrid, FORTRAC 3D, has a basic square flat pattern, with some wavy fibers going out of this base pattern that make it three-dimensional. The third membrane, HATE, differs from the previous two in its green color and in its very small square reticle pattern. The fourth option is a geomat called Megamat, characterized by the random position of the fibers (non woven). The first 3 membranes are made from

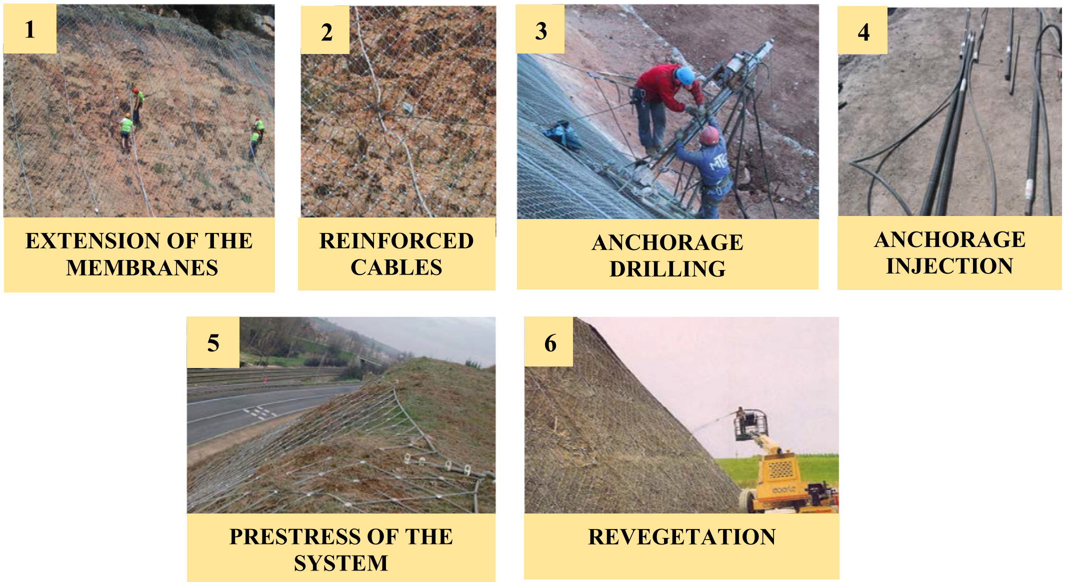


Fig. 1. Steps for the installation of a flexible membrane.

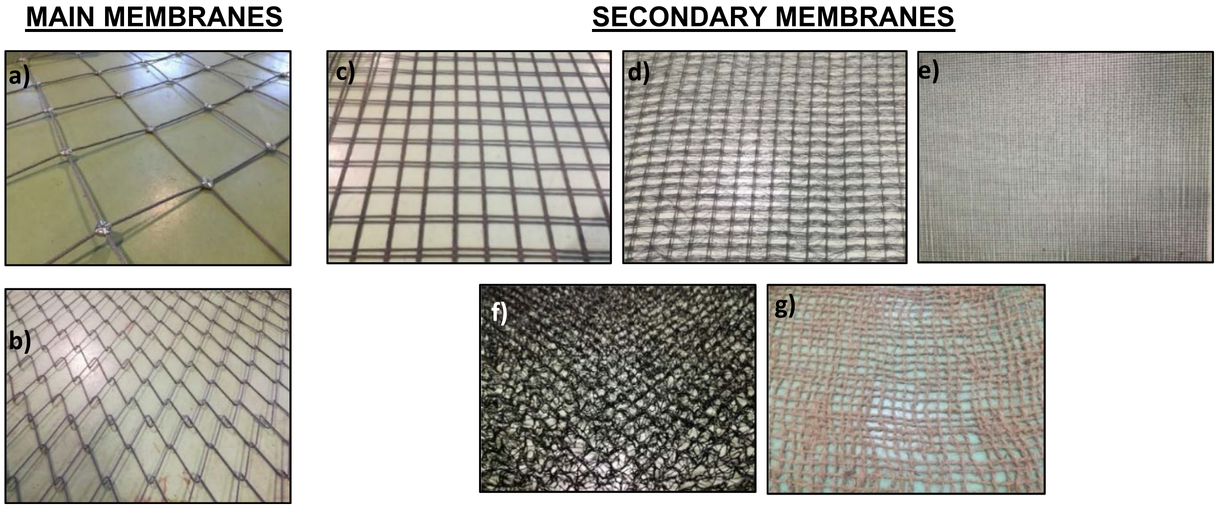


Fig. 2. Appearance of the main and secondary membranes: a) square cable net, b) wire mesh Tecco, c) Fortrac, d) Fortrac 3D, e) Hate, f) Megamat and g) Coconut Pavimant.

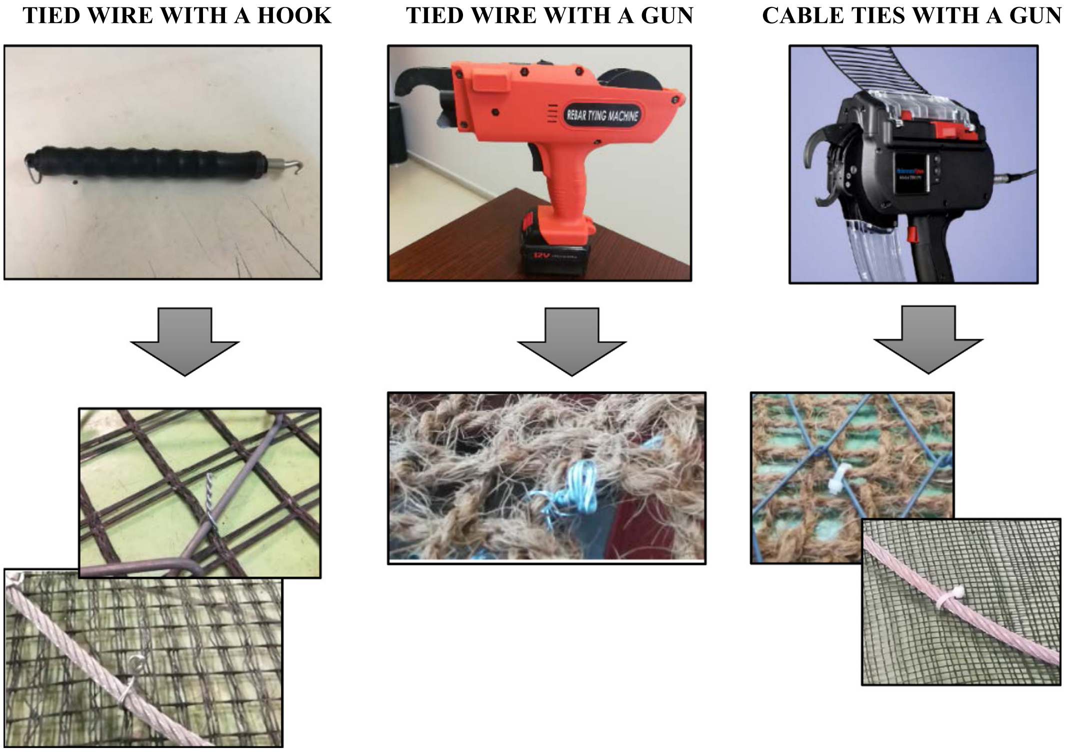


Fig. 3. Linking methods and final appearance: tied wire with a hook or with a gun, or cable ties with a gun.

polyethylene whilst the fourth one is made of polypropylene. Finally, coconut fiber mesh Pavimant is a biomat; that is, an organic membrane, with the fibers located in perpendicular directions, but not physically fixed in the intersection of each other. One factor considered in order to select these 5 membranes is that their strain must be equal or higher than the main membranes not to break before the main membranes do.

2.3. Linking methods

Two options were studied for the connection system between the main and secondary membrane. The first one is the use of tied wires using a hook or a gun. One drawback of these systems is that after rolling the wire, the process does not end, but the wire excess must be cut in order to prevent the wire from accidentally hooking up to other parts of the membrane during transportation. However, despite this inconvenience that causes a waste of time, these methods are one of the most effective to connect the main and secondary membranes.

The second option is the use of cable ties. To automate it, a cable tie gun can be used, that inserts the cable tie, tights it with the needed pressure and cuts the excess, doing all this in less than 3 s.

Although these linking methods seem to be very simple, they were selected due to their low connection time, which is the goal of the paper. Any other linking system studied implied a more complex execution and a higher connection time when compared with the three presented. Hence, they were discarded.

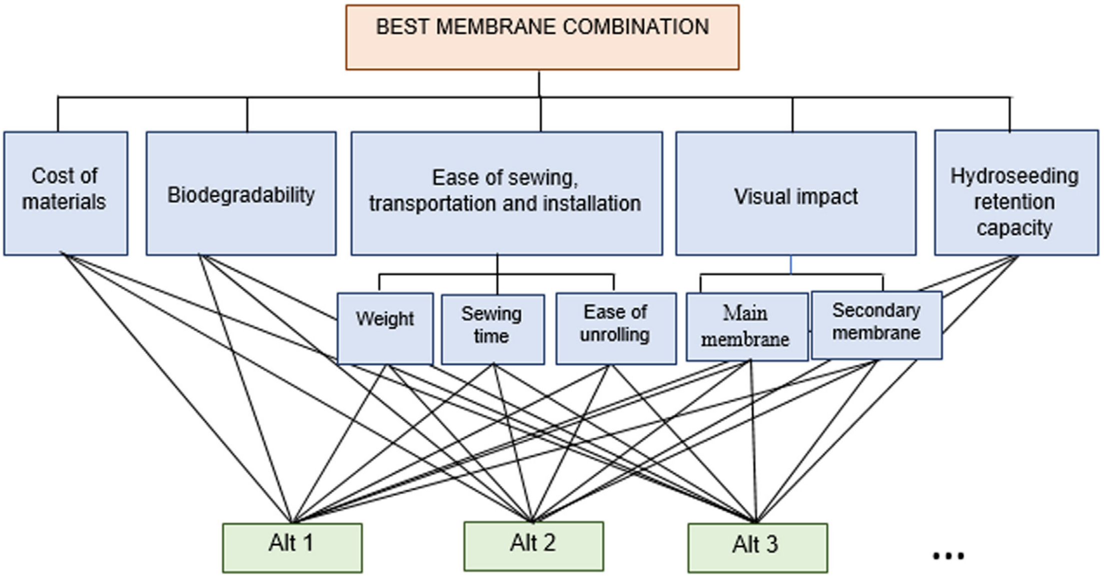


Fig. 4. Decision structure of the MDC problem. The first level (orange) represents the goal, the second and third level (blue) the criteria and sub-criteria and the fourth level (green) the alternatives to be evaluated.

3. Methodology: Multi-criteria decision analysis (MCDA)

The solution found to decide what the better combination of membranes is a linking method was used of multi-criteria decision analysis, which gives a hierarchy of all the alternatives studied. The first step to create a multi-criteria will be the definition of the objective, the definition of the criteria on which our decision will be based, and the definition of the alternatives to be studied, which will be found in Section 4 and 5.

3.1. Weighting the criteria: AHP

The Analytical Hierarchy Process (AHP) is based on the marking of the criteria doing pair-wise comparisons between them [16]. The scale of relative importance proposed by Saaty specifies that the values can go from 1 to 9 from equal to extreme importance of one criterion respect to the other (Table 1).

Using this range of values, the pairwise comparison matrix (1) can be constructed, in which the values of the diagonal are equal to 1 (meaning that we are comparing one criterion against itself, hence having the same importance), and the value given when comparing the criterion j with the criterion i (a_{ji}) must be the inverse of that obtained comparing the criterion i with j (a_{ij}).

$$A = \begin{bmatrix} a_{11} \cdots & a_{1j} \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{i1} \cdots & a_{ij} \cdots & a_{in} \\ \vdots & \vdots & \vdots \\ a_{n1} \cdots & a_{nj} \cdots & a_{nn} \end{bmatrix}_{ii}, a \;= 1, a_{ij} = \frac{1}{a_{ji}}, a_{ji} \neq 0 \tag{1}$$

Table 1
Saaty's scale of relative importance.

Level of importance	Linguistic Term
1	Equal
3	Moderate
5	Strong
7	Very strong
9	Extreme
2, 4, 6 and 8	Intermediate values

After that, the matrix A must be normalized, dividing each value of the matrix by the sum of all the values of its same column.

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{l=1}^{n} a_{lj}} \tag{2}$$

Finally, the weigh vector is calculated doing the average of all the components of the same row.

$$w_i = \frac{\sum_{l=1}^{n} a_{jl}}{n} \tag{3}$$

3.2. Weighting the alternatives

A basic step to do in both multi-criteria decision problems used for the alternatives weighting is to obtain the decision matrix, which should have the appearance of Table 2, where Xij is the value of the criterion i in the alternative j, and the last row describes the criterion as beneficial (B) or non-beneficial (NB). The term beneficial indicates that the higher the value of the criterion, the better, whilst non-beneficial means the opposite.

3.2.1. WASPAS

The Weighted Aggregated Sum Product Assessment (WASPAS) is the combination of weighted sum model (WSM) and weighted product model (WPM). It was developed by Zavadskas et al. 2012 [18] and it is one of the most robust MCDA methods.

The steps for the calculation using WASPAS method are the following:

(a) Normalize the weighted decision matrix for beneficial and non-beneficial criteria. Criteria is considered beneficial when the higher value is wanted and, on the contrary, is considered non-beneficial if the lower value is the best option. The normalization is carried out using Eqs. (4) and (5).

$$X'_{ij} = \frac{X_{ij}}{max(X_{ij})} \rightarrow Beneficial \tag{4}$$

Table 2
Construction of the initial decision matrix.

	Criterion 1	Criterion 2	Criterion ...	Criterion m
Alternative 1	X_{11}	X_{12}	$X_{1\dots}$	X_{1m}
Alternative 2	X_{21}	X_{22}	$X_{2..}$	X_{11}
Alternative ...	$X_{\dots 1}$	$X_{\dots 2}$	$X_{\dots\dots}$	X_{11}
Alternative n	X_{n1}	X_{n2}	X_{n3}	X_{nm}
	B/NB	B/NB	B/NB	B/NB

$$X'_{ij} = \frac{\min(X_{ij})}{X_{ij}} \rightarrow Non - beneficial \tag{5}$$

(b) Calculate the total relative importance using:

- The weighted sum model (WSM): it is defined as the sum of the product of the weight in the column j (Wj) and the normalized values of the previous point

$$A_i^{WSM} = \sum_{j=1}^{n} W_j \cdot X'_{ij} = Q_i^1 \tag{6}$$

- The weighted product model (WPM): it is calculated as the product of the normalized values powered to the weight of the criteria.

$$A_i^{WPM} = \prod_{j=1}^{n} X'^{W_j}_{ij} = Q_i^2 \tag{7}$$

(c) A joint generalized criterion of weighted aggregation of the additive and multiplicative methods is used to obtain the relative importance of each alternative, using Eq. (8).

$$Q_i = 0.5Q_i^1 + 0.5Q_i^2 \tag{8}$$

3.2.2. TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is based on the selection of the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution [19].

The calculation steps using TOPSIS method are the following:

(a) Normalize the decision matrix, by dividing each value by the square root of the sum of the vertical values squared.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \tag{9}$$

(b) Multiply each value of the normalized matrix (r_{ij}) by their weights (w_j) to obtain the weighted normalized decision matrix.

$$\begin{gathered} V = (v_{ij})_{m \cdot n} \\ v_{ij} = w_j r_{ij}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \\ m \end{gathered} \tag{10}$$

(c) Determine the ideal solution using Eq. (11) and the negative ideal solution using Eq. (12), considering the beneficial criteria set Ω_b and non-beneficial criteria set Ω_c.

$$V_j^+ = \{v_1^+, \cdots, v_2^+\} = \left\{\max_j v_{ij} | j \in \Omega_b\right\}, \left\{\min_j v_{ij} | j \in \Omega_c\right\} \tag{11}$$

$$V_j^- = \{v_1^-, \cdots, v_2^-\} = \left\{\min_j v_{ij} | j \in \Omega_b\right\}, \left\{\max_j v_{ij} | j \in \Omega_c\right\} \tag{12}$$

(d) Calculate the Euclidean distances of each alternative from the positive ideal solution and the negative ideal solution using Equations (13) and (14).

$$S_i^+ = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right)^{0.5} \tag{13}$$

$$S_i^- = \left(\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right)^{0.5} \tag{14}$$

(e) Calculate the relative closeness of each alternative to the ideal solution.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{15}$$

4. Selection of the alternatives

Once a range of components and linking methods were selected (see Section 2), the combination between them to create the different alternatives is quite high, and not fully appropriate for all the slope conditions. As an example, assuming that in our multi-criteria decision problem, the solution given is the use of a cable net of 300 mm of reticule with a Fortrac geogrid and connected with a tied wire. The cable net of 300 has the lower ultimate strength (Table 3) among all the main membranes included in the study. Hence, although being the best option in the MDMA, it is not suitable for the most demanding slopes. Having observed this problem, one could think that the easiest solution would be to include only the most resistant one as the main membrane, which is the TECCO® G65/4. However, the most resistant membrane is also the most expensive, so its use for a low demanding slope would imply an overprice with respect to a membrane more adjusted to the specifications of the slope to protect.

As specified in Table 3, under a distributed load test, the different options of main membranes can resist different maximum strengths with a wide amplitude between the lower and the higher. Hence, to solve the issues explained before the solution consists of carrying out three different MCDA for three levels of resistance: level A of around 45 kN/m2 (which would include the cable net of 300), level B of around 75 kN/m2 (which would include

Table 3
Ultimate strength on the distributed load tests of the four main membranes studied.

Membrane type	Ultimate strength (kN/m^2)
Cable net 300x300	45.7
Cable net 200x200	72.5
TECCO® G65/3	80.0
TECCO® G65/4	126.7

the cable net of 200 and the TECCO® G65/3) and level C of around 125 kN/m2 (with the TECCO® G65/4). Depending on the required ultimate strength of the solution, the decision will be made between the alternatives of Level A, B or C. In Table 4, Table 5 and Table 6 alternatives for each level are shown [1,20].

This mechanical parameter, ultimate strength, derived from a distributed load test, is commonly provided by manufacturers on their catalogues to define the strength of their products. For design purposes, this parameter could be related with the ultimate tensile strength in order to perform numerical simulations that model the interaction between flexible systems and unstable slopes as suggested in [17].

5. Selection of the criteria

The criteria used to evaluate the alternatives are:

- **Cost of materials**: It is a numerical criterion expressed in €/m^2, that includes cost of the principal and secondary membrane. Costs in general is always a parameter to minimize, since we are looking for an inexpensive product. Hence, the lower the cost, the better.
- **Biodegradability**: Society is gradually becoming more environment-conscious, so biodegradable solutions that are able to disappear in a few years by the time revegetation appears and retains the soil is better than others that stay for decades and even centuries. Biodegradability is a numerical criterion expressed in years of service life. The longer service life, the worse.
- **Ease of sewing, transportation and installation**: This criterion can be divided in 3 subcriteria:

  - o **Weight of the system**: It is a numerical criterion, expressed in kg/m^2, that embraces the sum of both membranes, and the lower the weight the easiest the handling, transport and installation on the slope.
  - o **Ease of unrolling:** It is related to how many difficulties there will be when the set arrives to the top of the slope and it is time to unroll it. It is a categorical criterion in which values from 1 to 4 were given. The value 1 is given when the unrolling presents complex hooks that do not let the set unroll for its installation; 2 when hooks appear but are easily removable; 3 is given when there are not hooks during the unrolling but the membranes extended present some wrinkles, and finally 4 is the value given when no hooks or wrinkles appear at all. The easiest and less problematic the unrolling the shortest the installation time.
  - o **Sewing time:** It can be defined as the time one square meter of membranes are connected using the methods commented in the previous slides, like hooks or guns. This value is extracted from tests made at the laboratory. A lower sewing time will reduce costs and allow a higher supply capacity of the Company

Table 4
Characteristics of the alternatives on the level 45 kN/m2.

Level A: 45 kN/m^2			
Alternatives	Principal membrane	Secondary membrane	Connection type
1	Cable net 300	Geomat Fortrac	Tie wire-Gun
2	Cable net 300	Geomat Fortrac	Cable tie A-Gun
3	Cable net 300	Geomat Fortrac 3D	Tie wire-Gun
4	Cable net 300	Geomat Fortrac 3D	Cable tie A-Gun
5	Cable net 300	Coconut Pavimant coarse	Tie wire-Gun
6	Cable net 300	Coconut Pavimant coarse	Cable tie A-Gun
7	Cable net 300	Geomat HaTe	Cable tie B-Hand
8	Cable net 300	Megamat 10	Tie wire-Hook

Table 5
Characteristics of the alternatives on the level 75 kN/m2.

Level B: 75 kN/m^2			
Alternatives	Principal membrane	Secondary membrane	Connection type
1	Cable net 200	Geomat Fortrac	Tie wire-Gun
2	Cable net 200	Geomat Fortrac	Cable tie A-Gun
3	Cable net 200	Geomat Fortrac 3D	Tie wire-Gun
4	Cable net 200	Geomat Fortrac 3D	Cable tie A-Gun
5	Cable net 200	Coconut Pavimant coarse	Tie wire-Gun
6	Cable net 200	Coconut Pavimant coarse	Cable tie A-Gun
7	Cable net 200	Geomat HaTe	Cable tie B-Hand
8	Cable net 200	Megamat 10	Tie wire-Hook
9	TECCO® G65/3	Geomat Fortrac	Tie wire-Gun
10	TECCO® G65/3	Geomat Fortrac	Cable tie A-Gun
11	TECCO® G65/3	Geomat Fortrac 3D	Tie wire-Gun
12	TECCO® G65/3	Geomat Fortrac 3D	Cable tie A-Gun
13	TECCO® G65/3	Coconut Pavimant coarse	Tie wire-Gun
14	TECCO® G65/3	Coconut Pavimant coarse	Cable tie A-Gun
15	TECCO® G65/3	Geomat HaTe	Cable tie B-Hand
16	TECCO® G65/3	Megamat 10	Tie wire-Hook

Table 6
Characteristics of the alternatives on the level 125 kN/m2.

Level C: 125 kN/m^2			
Alternatives	Principal membrane	Secondary membrane	Connection type
1	TECCO® G65/4	Geomat Fortrac	Tie wire-Gun
2	TECCO® G65/4	Geomat Fortrac	Cable tie A-Gun
3	TECCO® G65/4	Geomat Fortrac 3D	Tie wire-Gun
4	TECCO® G65/4	Geomat Fortrac 3D	Cable tie A-Gun
5	TECCO® G65/4	Coconut Pavimant coarse	Tie wire-Gun
6	TECCO® G65/4	Coconut Pavimant coarse	Cable tie A-Gun
7	TECCO® G65/4	Geomat HaTe	Cable tie B-Hand
8	TECCO® G65/4	Megamat 10	Tie wire-Hook

- **Visual impact**
  - o **Of the main membrane:** It is a numerical criterion obtained by calculating the area of land covered by the membrane in a square meter in each case, so it is expressed in mm^2/m^2. The lower the visual impact the better.
  - o **Of the secondary membrane:** Geomats with colors which easily camouflage or blend with the soil or vegetation are better. The visual impact of the secondary membrane is a categorical parameter that goes from 1 (the lowest visual impact) to 5 (the highest visual impact). The rank from 1 to 5 for the secondary membranes studied is: 1 for coconut, 2 for Hate, 3 for Fortrac 3D, 4 for Fortrac and 5 for Megamat.

- **Hydroseeding retention capacity**: The highest coefficient of gaps of the secondary membrane helps the hydroseeding to fix to the soil and membrane better. This is a categorical parameter valued from 1 to 3 from bad retention capacity to good corresponding 1 to Fortrac, 2 to Coconut, Hate and Fortrac 3D and 3 to Megamat.

A summary of the criteria features is shown in Table 7. The values of the quantitative criteria are extracted from data sheets or experimental tests.

6. Results

6.1. Results of the criteria weightings

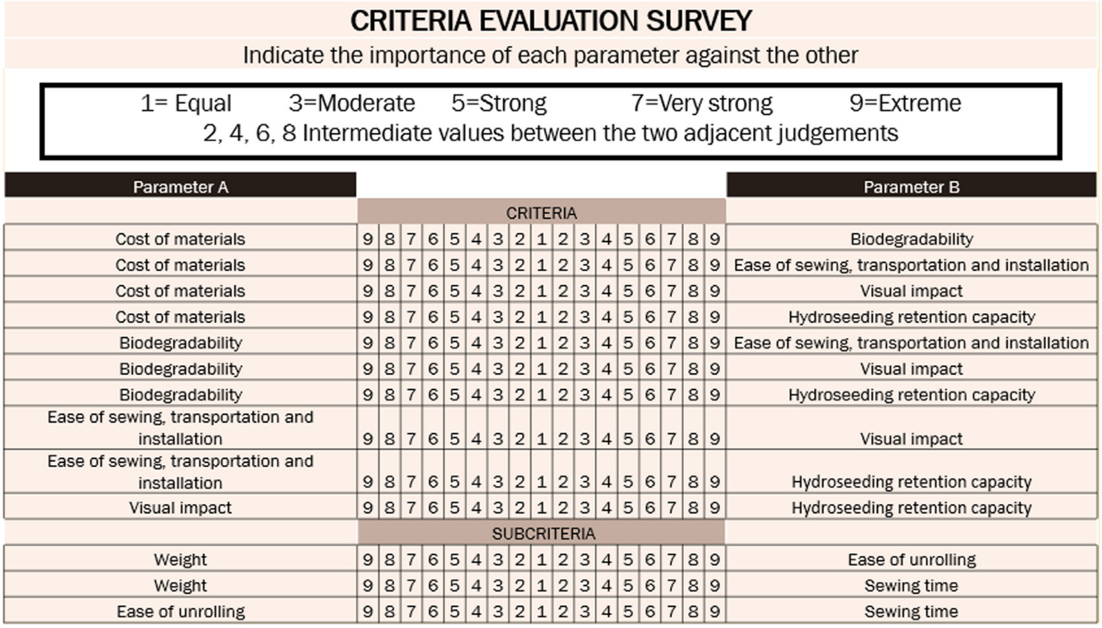
To obtain a reliable weighting of the criteria and minimize the subjectivity and bias, the survey of Fig. 5 was sent to experts on the topic, such as counsellors of infrastructures, workers and CEOS from companies of the field and researchers from the University of Cantabria that developed their thesis on these type of systems. In total, 13 surveys were considered.

Following the steps of the Section 3.1, weights for each criterion were calculated. The final weights are shown on Table 8 as a result of averaging the weights extracted for the surveys of each individual. Each column represents a criterion, being C the cost, Bio the biodegradability, W the weight of the system, E.U. the easiness of unrolling, S.T the sewing time, V.I.1 the visual impact of the main membrane, V.I.2 the visual impact of the secondary membrane and Hyd the hydroseeding retention capacity.

The most important criterion among all resulted to be the hydroseeding retention capacity. This result is coherent, specially knowing that when dealing with soil slopes, the growth of vegetation would add more resistance to the protection system making it even more reliable. The cost of the system is placed in the second position of the rank. Although the differences of cost of a square meter of a secondary membrane are not high, knowing that slope protection may entail covering a massive area of land, it could make a critical difference. The third position on the ranking is for biodegradability. On the other hand, the lowest values of the criteria are found on the visual impact of the membranes. These could be due to the fact that the surveys were carried out mostly by technicians who are more focused on the practical behaviour of the solution, rather than the visual result, which could be a more important criterion for the users of the areas protected.

Table 7
Properties of the criteria.

Criteria	Qualitative/ Quantitative	Units (only quantitative criteria)	Rank (only qualitative criteria)	Beneficial/non beneficial
Cost of materials	Quantitative	€/m2		Non beneficial
Biodegradability	Quantitative	years		Non beneficial
Weight of the system	Quantitative	Kg/m2		Non beneficial
Ease of unrolling	Qualitative		1 (most difficult) to 4(easiest)	Beneficial
Sewing time	Quantitative	s		Non beneficial
Visual impact of main membrane	Quantitative	mm2/m2		Non beneficial
Visual impact of secondary membrane	Qualitative		1 (lowest) to 5 (highest)	Non beneficial
Hydroseeding retention capacity	Qualitative		1 (lowest) to 3 (highest)	Beneficial



CRITERIA EVALUATION SURVEY

Indicate the importance of each parameter against the other

1= Equal 3=Moderate 5=Strong 7=Very strong 9=Extreme
2, 4, 6, 8 Intermediate values between the two adjacent judgements

Parameter A																		Parameter B
	CRITERIA																	
Cost of materials	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biodegradability
Cost of materials	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ease of sewing, transportation and installation
Cost of materials	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Visual impact
Cost of materials	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hydroseeding retention capacity
Biodegradability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ease of sewing, transportation and installation
Biodegradability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Visual impact
Biodegradability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hydroseeding retention capacity
Ease of sewing, transportation and installation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Visual impact
Ease of sewing, transportation and installation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hydroseeding retention capacity
Visual impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Hydroseeding retention capacity
	SUBCRITERIA																	
Weight	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ease of unrolling
Weight	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sewing time
Ease of unrolling	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sewing time

Fig. 5. Survey sent to experts on the topic to obtain the criteria weighting.

Table 8
Final weights of the criteria.

	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
Weight	0,186	0,132	0,076	0,125	0,116	0,068	0,068	0,23

6.2. Results of the alternatives weightings

6.2.1. Initial decision matrix

Table 9, Table 10 and Table 11 represent the initial decision matrix for the three levels of resistance, from which WASPAS and TOPSIS methods are applied.

One detail that can be noted is that there is no variation on the values of V.I.1. (visual impact on the main membrane) among the alternatives of Table 9 as well as among the alternatives in Table 11. This occurs because the main membrane used in each table is the same. However, in Level B two different values can be seen, since two main membranes are included in the alternatives. Although the subcriterion V.I.1 could be removed from the levels A and C, it was kept in order to maintain the same criterion weightage in the three levels. The results will not be damaged by this decision; at the time the decision matrix is normalized, each value of the column corresponding to V.I.1 will become 1 and the final weightage of the alternatives will be equally influenced by these criteria. Biodegradability of the alternatives is not included in these tables but explained in the next section.

6.2.2. Influence of the biodegradability on the MDMA

One of the main problems faced on by this study is the lack of information -or in some cases its vagueness- relative to the degradability of the secondary membranes. Due to this, four different scenarios were considered for the MDMA. In Table 12 the relations of the degradability among membranes are shown for all the scenarios. Scenario 1 corresponds to the minimum values of this parameter given by the manufacturers. As for Scenarios 2 and 3, Megamat manufacturer gave the authors a minimum durability of 5 years but with the warning it could last quite a longer amount of time although the standards only required tests for 5 years [21]. Therefore, this mat is the most unknown concerning this criterion. The material with which is made, polypropylene, can degrade with

Table 9
Initial decision matrix for the alternatives on the level 45 kN/m2.

Level A: 45 kN/m^2								
Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	10.53	See Table 12 for the different scenarios	2.36	2	1.933	45254.4	4	1
2	10.53		2.36	4	0.933	45254.4	4	1
3	11.88		2.34	4	1.933	45254.4	3	3
4	11.88		2.34	4	0.933	45254.4	3	3
5	10.2		2.53	3	1.933	45254.4	1	2
6	10.2		2.53	3	0.933	45254.4	1	2
7	10.75		2.26	4	3.400	45254.4	2	2
8	10.3		2.43	4	9.830	45254.4	5	3
	NB	NB	NB	B	NB	NB	NB	B

Table 10
Initial decision matrix for the alternatives on the level 75 kN/m2.

Level B: 75 kN/m^2								
Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	19.53	See Table 12 for the different scenarios	4.03	2	1.933	79749.76	4	1
2	19.53		4.03	4	0.933	79749.76	4	1
3	20.88		4.01	4	1.933	79749.76	3	3
4	20.88		4.01	4	0.933	79749.76	3	3
5	19.2		4.2	3	1.933	79749.76	1	2
6	19.2		4.2	3	0.933	79749.76	1	2
7	19.75		3.93	4	3.400	79749.76	2	2
8	19.3		4.1	4	9.830	79749.76	5	3
9	21.53		1.88	1	1.933	85,680	4	1
10	21.53		1.88	3	0.933	85,680	4	1
11	22.88		1.86	3	1.933	85,680	3	3
12	22.88		1.86	4	0.933	85,680	3	3
13	21.2		2.05	3	1.933	85,680	1	2
14	21.2		2.05	4	0.933	85,680	1	2
15	21.75		1.78	4	3.400	85,680	2	2
16	21.3		1.95	4	9.830	85,680	5	3
	NB	NB	NB	B	NB	NB	NB	B

Table 11
Initial decision matrix for the alternatives on the level 120 kN/m2.

Level C: 120 kN/m^2								
Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	48.53	See Table 12 for the different scenarios	2.98	1	1.933	114,240	4	1
2	48.53		2.98	3	0.933	114,240	4	1
3	49.88		2.96	3	1.933	114,240	3	3
4	49.88		2.96	4	0.933	114,240	3	3
5	48.2		3.15	3	1.933	114,240	1	2
6	48.2		3.15	4	0.933	114,240	1	2
7	48.75		2.88	4	3.400	114,240	2	2
8	48.3		3.05	4	9.830	114,240	5	3
	NB	NB	NB	B	NB	NB	NB	B

the sun light radiation. Hence, its degradation time will be lower than those with a polyethylene base, such as Fortrac, Fortrac 3D or HaTe. Due to this, scenarios 2 and 3 keep all the durabilities the same except the one of Megamat, which takes values of 20 and 50 years, respectively. At last, since all the durability values are minimums, Scenario 4 takes higher than the minimum durability values, that follow the same order in the life time (lowest life goes to Pavimant, second is Megamat, and so on until reaching the highest life time of geomat Fortrac 3D), but does not follow the same ratio between them than in the previous scenarios.

In Table 13, Table 14 and Table 15 the results of the MCDA are shown, using the normalized matrixes of Section 6.2.1 and including the column of biodegradability for each scenario.

Concerning the level of energy of 45 kN/m^2, alternatives 5 and 6 are in all cases in the positions 1 and 2, respectively. This indicates that the best secondary membrane is the coconut mesh Pavimant, and the best attaching method the cable tie machine. Results start to change from position 3 onwards in the ranking. The scenario 1, in which the durability of the Megamat is of 5 years, gives as the third best option alternative 8 (the one that includes the Megamat as a secondary net) using WASPAS method. The sewing method is manual using tie wires, since there is no other possible attachment method for this combination. However, TOPSIS gives to alternative 8 the 7th position, quite far from the WASPAS result. In all the cases excepting the WASPAS analysis of scenario 1, mentioned before, the third and fourth position are the alternatives 4 and 3, respectively, which use Fortrac 3D, and again giving priority to the cable ties rather than the tie wires as connection method. The worst configuration is the one of alternative 1, in which Fortrac secondary membrane is used and sewed to the cable net with tie wires. The only exception to this behavior appears in the TOPSIS analysis on the scenario 3 in which the lowest score is obtained by alternative 8 (that uses Megamat), behind alternative 1, the most generally unfavorable. Comparing WASPAS and TOPSIS methodologies, the highest discrepancies appear in alternative 8, in which differences could be up to 4 positions in the ranking. Both methodologies concur that the best solutions are alternative 6 followed by alternative 5, whilst in the rest of the ranking some low

Table 12
Scenarios of the durability of the secondary membranes.

Degradability (years)				
	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Fortrac	100	100	100	150
Fortrac 3D	120	120	120	200
Pavimant	2	2	2	3
HaTe	100	100	100	120
Megamant	5	20	50	40

Table 13
Results and ranking of alternatives from the 4 scenarios subjected to WASPAS and TOPSIS methods in the level of energy A (45 kN/m^2).

ALT	SCENARIO1				SCENARIO 2				SCENARIO 3				SCENARIO 4			
	WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS	
	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank
1	0.444	8	0.467	8	0.444	8	0.468	8	0.444	8	0.469	7	0.444	8	0.473	8
2	0.538	7	0.515	6	0.538	7	0.515	6	0.538	7	0.516	6	0.538	7	0.520	6
3	0.609	5	0.627	4	0.609	4	0.627	4	0.609	4	0.631	4	0.606	4	0.611	4
4	0.661	4	0.645	3	0.661	3	0.646	3	0.661	3	0.650	3	0.657	3	0.629	3
5	0.813	2	0.746	2	0.813	2	0.746	2	0.813	2	0.745	2	0.813	2	0.750	2
6	0.878	1	0.765	1	0.878	1	0.764	1	0.878	1	0.764	1	0.878	1	0.768	1
7	0.555	6	0.548	5	0.555	6	0.548	5	0.555	6	0.551	5	0.562	6	0.592	5
8	0.678	3	0.502	7	0.608	5	0.487	7	0.575	5	0.456	8	0.597	5	0.490	7

Table 14
Results and ranking of alternatives from the 4 scenarios subjected to WASPAS and TOPSIS methods in the level of energy A (75 kN/m^2).

ALT	SCENARIO1				SCENARIO 2				SCENARIO 3				SCENARIO 4			
	WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS	
	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank
1	0.416	15	0.466	15	0.416	15	0.466	15	0.416	15	0.467	14	0.416	15	0.471	15
2	0.508	13	0.521	11	0.508	13	0.521	11	0.508	13	0.522	11	0.508	13	0.525	11
3	0.584	9	0.628	7	0.584	8	0.628	7	0.584	7	0.632	7	0.581	7	0.612	7
4	0.634	8	0.645	6	0.634	6	0.645	6	0.634	6	0.649	6	0.631	6	0.630	6
5	0.773	4	0.727	4	0.773	4	0.726	4	0.773	4	0.725	4	0.773	4	0.731	4
6	0.836	2	0.744	3	0.836	2	0.744	3	0.836	2	0.743	3	0.836	2	0.748	3
7	0.524	12	0.554	10	0.524	12	0.555	10	0.524	12	0.557	10	0.531	12	0.595	10
8	0.643	7	0.508	14	0.575	10	0.494	14	0.545	10	0.466	15	0.565	10	0.496	14
9	0.400	16	0.462	16	0.400	16	0.462	16	0.400	16	0.463	16	0.400	16	0.467	16
10	0.501	14	0.516	12	0.501	14	0.517	12	0.501	14	0.518	12	0.501	14	0.521	12
11	0.578	10	0.626	8	0.578	9	0.626	8	0.578	8	0.630	8	0.575	9	0.610	8
12	0.653	6	0.653	5	0.653	5	0.654	5	0.653	5	0.658	5	0.650	5	0.637	5
13	0.791	3	0.748	2	0.791	3	0.748	2	0.791	3	0.747	2	0.791	3	0.752	2
14	0.886	1	0.780	1	0.886	1	0.780	1	0.886	1	0.779	1	0.886	1	0.784	1
15	0.542	11	0.566	9	0.542	11	0.566	9	0.542	11	0.568	9	0.549	11	0.607	9
16	0.659	5	0.515	13	0.591	7	0.502	13	0.559	9	0.474	13	0.580	8	0.504	13

Table 15
Results and ranking of alternatives from the 4 scenarios subjected to WASPAS and TOPSIS methods in the level of energy A (120 kN/m^2).

ALT	SCENARIO1				SCENARIO 2				SCENARIO 3				SCENARIO 4			
	WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS		WASPAS		TOPSIS	
	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank	Qi	Rank	Pi	Rank
1	0.417	8	0.455	8	0.417	8	0.455	8	0.417	8	0.456	8	0.417	8	0.460	8
2	0.519	7	0.512	6	0.519	7	0.513	6	0.519	7	0.514	6	0.519	7	0.517	6
3	0.601	5	0.626	4	0.601	5	0.626	4	0.601	4	0.630	4	0.597	5	0.610	4
4	0.677	4	0.655	3	0.677	3	0.655	3	0.677	3	0.659	3	0.673	3	0.638	3
5	0.814	2	0.748	2	0.814	2	0.748	2	0.814	2	0.747	2	0.814	2	0.752	2
6	0.911	1	0.782	1	0.911	1	0.781	1	0.911	1	0.781	1	0.911	1	0.785	1
7	0.560	6	0.562	5	0.560	6	0.563	5	0.560	6	0.565	5	0.567	6	0.605	5
8	0.680	3	0.512	7	0.610	4	0.499	7	0.577	5	0.470	7	0.599	4	0.501	7

differences could appear, but never higher than one position between cases on the same scenario.

A similar analysis to that of the level 45 kN/m^2 could be done in the highest level of energy, 120 kN/m^2. This is logical considering that the secondary membranes and the connecting technique are the same, and the only change is the main membrane, changing from a cable net to the wire mesh TECCO® G65/4. There are only 3 differences with respect to the lowest level. In WASPAS results on scenario 2 and 4, positions 4 and 5 are changed. Eventually, for this level of energy, the last position in the TOPSIS method on scenario 3 corresponds to alternative 1, agreeing this time with all the other results of the most unfavorable option.

It must be noted that TOPSIS results for all the scenarios in both levels of energy (45 and 120 kN/m2) are the same with the only exception of the last two positions of the Scenario 3 on the lowest level of energy, which are inverted.

As for the level of energy with a higher number of alternatives, that is 75 kN/m^2, the best alternative in all the scenarios and both MDMA methods is alternative 14, that as expected after having analyzed the other energy levels, uses the organic mat Pavimant and a cable ties connection system. In addition, this alternative, that uses the wire mesh TECCO G65/3 has priority over alternative 6, which has the same configuration as alternative 14 but uses a cable net instead. In all cases the alternatives with the Pavimant are in the first 4 positions and again, alternatives with the Fortrac geomat using tie wires are in the last 2 positions. The highest variability is found in alternatives with geomats HATE and Megamat. As it happened with the other energy levels, the second secondary membrane after Pavimant is Fortrac 3D connected with a cable tie machine, with the 5 and 6 position in the ranking in all cases except in the WASPAS analysis of Scenario 1, where Megamat gains the 5th position.

7. Conclusions

Multi-criteria decision analysis is a very useful methodology used in this work to find out the best combination of main membrane, secondary membrane and connection method taking into account five different criteria and 5 subcriteria, simultaneously.

The division of the evaluation considering 3 levels of energy is needed in order to limit the number of alternatives and adjust them to the level where it could best fit. In this way, overprice and over-resistance are avoided.

The variability in biodegradability taking into account the 4 scenarios does not influence the first two positions of the MCDA for any of the two methodologies used; that is, WASPAS and TOPSIS. TOPSIS is barely influenced by this criterion with only a change in two positions at the end of the ranking of scenario 3 in all the energy levels.

Although there exist some discrepancies on the intermediate part of the ranking, WASPAS and TOPSIS methodologies offer similar results regarding the most favorable and most unfavorable positions.

The Pavimant organic mat is the most important when it comes to protecting soil slopes. The biodegradability of the secondary membrane is considered very important since they reduce the environmental impact and, together with hydroseeding, contribute to the creation of vegetation that favors the reduction of slides thanks to the action of the plant roots. In rock slopes; however, biodegradability would take a back seat, and it would be more important that the secondary membrane withstanding the passage of time to retain small rocks, preventing them from slipping into the gaps in the main membrane and helping distribute the load to the entire main network to the anchorages.

Although the use of tie wire gun appears to be the most visually appealing and as well as the most industrial-like and professional solution, it is significantly penalized due to the fact that after the use of the gun or hook, it is necessary to cut off the excess so that when the set is rolled up for transport, it does not get caught between the different layers of the roll. However, the use of a cable tie gun is much faster since it automatically cuts the excess. Even manual cable tie placement has an installation time similar to that used by the wire tie gun. All this means that the most favorable solutions are always those using cable ties compared to the same alternative but using tie wire.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Multi-criteria Decision Analysis of Scenario 1 and level A of resistance (45 kN/m2) using WASPAS method

The calculation starts with the initial decision matrix (Table 16).

Table 16
Initial decision matrix for level A of resistance and Scenario 1.

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	10.53	100	2.36	2	1.933	45254.4	4	1
2	10.53	100	2.36	4	0.933	45254.4	4	1
3	11.88	120	2.34	4	1.933	45254.4	3	3
4	11.88	120	2.34	4	0.933	45254.4	3	3
5	10.2	2	2.53	3	1.933	45254.4	1	2
6	10.2	2	2.53	3	0.933	45254.4	1	2
7	10.75	100	2.26	4	3.400	45254.4	2	2
8	10.3	5	2.43	4	9.830	45254.4	5	3
	NB	NB	NB	B	NB	NB	NB	B

Using Eqs. (4) and (5) for Beneficial and Non-Beneficial criteria respectively, the normalized matrix is obtained (Table 17).

Table 17
Normalized matrix on WASPAS for level A of resistance and Scenario 1.

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	0.969	0.020	0.958	0.500	0.483	1.000	0.250	0.333
2	0.969	0.020	0.958	1.000	1.000	1.000	0.250	0.333
3	0.859	0.017	0.966	1.000	0.483	1.000	0.333	1.000
4	0.859	0.017	0.966	1.000	1.000	1.000	0.333	1.000
5	1.000	1.000	0.893	0.750	0.483	1.000	1.000	0.667
6	1.000	1.000	0.893	0.750	1.000	1.000	1.000	0.667
7	0.949	0.020	1.000	1.000	0.275	1.000	0.500	0.667
8	0.990	0.400	0.930	1.000	0.095	1.000	0.200	1.000

$W_j \cdot X'_{ij}$ is calculated in each cell, and using Eq. (6), Q_i^1 is calculated and included in the last column (Table 18).

Table 18
Matrix of $W_j \cdot X'_{ij}$ and Q_i^1 for each alternative (for level A of resistance and Scenario 1).

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd	Q1i
1	0.1802	0.0026	0.0728	0.0625	0.0560	0.0680	0.0170	0.0767	0.536
2	0.1802	0.0026	0.0728	0.1250	0.1160	0.0680	0.0170	0.0767	0.658
3	0.1597	0.0022	0.0734	0.1250	0.0560	0.0680	0.0227	0.2300	0.737
4	0.1597	0.0022	0.0734	0.1250	0.1160	0.0680	0.0227	0.2300	0.797
5	0.1860	0.1320	0.0679	0.0938	0.0560	0.0680	0.0680	0.1533	0.825
6	0.1860	0.1320	0.0679	0.0938	0.1160	0.0680	0.0680	0.1533	0.885
7	0.1765	0.0026	0.0760	0.1250	0.0318	0.0680	0.0340	0.1533	0.667
8	0.1842	0.0528	0.0707	0.1250	0.0110	0.0680	0.0136	0.2300	0.755

$X'^{W_j}_{ij}$ is calculated in each cell, and using Eq. (7), Q_i^2 is calculated and included in the last column (Table 19).

Table 19
Matrix of $X'^{W_j}_{ij}$ and Q_i^2 for each alternative (for level A of resistance and Scenario 1).

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd	**Q2i**
1	0.9941	0.5967	0.9967	0.9170	0.9190	1.0000	0.9100	0.7767	0.352
2	0.9941	0.5967	0.9967	1.0000	1.0000	1.0000	0.9100	0.7767	0.418
3	0.9720	0.5825	0.9974	1.0000	0.9190	1.0000	0.9280	1.0000	0.482
4	0.9720	0.5825	0.9974	1.0000	1.0000	1.0000	0.9280	1.0000	0.524
5	1.0000	1.0000	0.9915	0.9647	0.9190	1.0000	1.0000	0.9110	0.801
6	1.0000	1.0000	0.9915	0.9647	1.0000	1.0000	1.0000	0.9110	0.871
7	0.9903	0.5967	1.0000	1.0000	0.8607	1.0000	0.9540	0.9110	0.442
8	0.9982	0.8861	0.9945	1.0000	0.7610	1.0000	0.8963	1.0000	0.600

Finally, Eq. (8) is applied to get the score needed to make the rank (Table 20).

Table 20
Q_j and final rank of the alternatives for WASPAS for level A of resistance and Scenario 1.

Alternative	Qi	RANK
1	0.444	8
2	0.538	7
3	0.609	5
4	0.661	4
5	0.813	2
6	0.878	1
7	0.555	6
8	0.678	3

Multi-criteria Decision Analysis of Scenario 1 and level A of resistance (45 kN/m2) using TOPSIS method
The initial decision matrix is the same as the one used for WASPAS (Table 16)
The normalized matrix is then obtained using Eq. (9) (Table 21).

Table 21
Normalized matrix on TOPSIS for level A of resistance and Scenario 1.

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	0.345	0.412	0.348	0.198	0.175	0.354	0.444	0.156
2	0.345	0.412	0.348	0.396	0.084	0.354	0.444	0.156
3	0.389	0.495	0.345	0.396	0.175	0.354	0.333	0.469
4	0.389	0.495	0.345	0.396	0.084	0.354	0.333	0.469
5	0.334	0.008	0.373	0.297	0.175	0.354	0.111	0.312
6	0.334	0.008	0.373	0.297	0.084	0.354	0.111	0.312
7	0.352	0.412	0.334	0.396	0.308	0.354	0.222	0.312
8	0.337	0.021	0.359	0.396	0.890	0.354	0.556	0.469

Each cell of the normalized matrix is multiplied for the weight of the criteria to obtain the weighted normalized matrix (Table 22).

Table 22
Weighted normalized matrix V for level A of resistance and Scenario 1.

Alt	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
1	0.0641	0.0544	0.0265	0.0248	0.0203	0.0240	0.0302	0.0359
2	0.0641	0.0544	0.0265	0.0495	0.0098	0.0240	0.0302	0.0359
3	0.0723	0.0653	0.0262	0.0495	0.0203	0.0240	0.0227	0.1078
4	0.0723	0.0653	0.0262	0.0495	0.0098	0.0240	0.0227	0.1078
5	0.0621	0.0011	0.0284	0.0371	0.0203	0.0240	0.0076	0.0718
6	0.0621	0.0011	0.0284	0.0371	0.0098	0.0240	0.0076	0.0718
7	0.0654	0.0544	0.0254	0.0495	0.0357	0.0240	0.0151	0.0718
8	0.0627	0.0027	0.0273	0.0495	0.1032	0.0240	0.0378	0.1078

Then, the ideal solution using Eq. (11) and the negative ideal solution using Eq. (12) is determined depending on whether the criteria is beneficial or non-beneficial (Table 23).

Table 23
Matrix of ideal and negative ideal solutions for level A of resistance and Scenario 1.

	C	Bio	W	E.U.	S.T.	V.I.1	V.I.2	Hyd
	Non-benef	Non-Benef	Non-benef	Benef	Non-benef	Non-benef	Non-benef	Benef
Vj+	0.0621	0.0011	0.0254	0.0495	0.0098	0.0240	0.0076	0.1078
Vj-	0.0723	0.0653	0.0284	0.0248	0.1032	0.0240	0.0378	0.0359

Following, Euclidean distances S_i^+ and S_i^- are calculated using expressions (13) and (14) (Table 24).

Table 24
Matrix of $S_i^+$and S_i^- for level A of resistance and Scenario 1.

Alternative	Si+	Si-
1	0.096	0.084
2	0.092	0.098
3	0.068	0.114
4	0.067	0.121
5	0.040	0.116
6	0.038	0.124
7	0.070	0.085
8	0.098	0.099

Lastly, the score $P_i$is obtained, from which a rank of the alternatives can be done (Table 25).

Table 25
P_i and final rank of the alternatives for TOPSIS for level A of resistance and Scenario 1.

Alternative	Pi	RANK
1	0.467	8
2	0.515	6
3	0.627	4
4	0.645	3
5	0.746	2
6	0.765	1
7	0.548	5
8	0.502	7

Multi-criteria Decision Analysis using WASPAS and TOPSIS in other Scenarios and levels of resistance.

The previous sections of the appendix correspond only to one specific case. The rest of the cases are calculated in the same way, except for the only change of modifying the biodegradability column of the initial decision matrix to the following (Table 26 and 27):

Table 26
Biodegradability values for the different alternatives to be used on the initial decision matrix of levels A and C of resistance (45 kN/m^2 and 125 kN/m^2).

	Biodegradability			
Alternative	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	100	100	100	150
2	100	100	100	150
3	120	120	120	200
4	120	120	120	200
5	2	2	2	3
6	2	2	2	3
7	100	100	100	120
8	5	20	50	40

Table 27
Biodegradability values for the different alternatives to be used on the initial decision matrix of levels B of resistance (75 kN/m^2).

	Biodegradability			
Alternative	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	100	100	100	150
2	100	100	100	150
3	120	120	120	200
4	120	120	120	200
5	2	2	2	3
6	2	2	2	3
7	100	100	100	120
8	5	20	50	40
9	100	100	100	150
10	100	100	100	150
11	120	120	120	200
12	120	120	120	200
13	2	2	2	3
14	2	2	2	3
15	100	100	100	120
16	5	20	50	40

References

[1] Castro FD. Estudio y análisis de las membranas flexibles como elemento de soporte para la estabilización de taludes y laderas de suelos y/o materiales sueltos. Santander: Universidad de Cantabria; 2000 [Ph.D. thesis].

[2] Blanco-Fernandez E, Castro-Fresno D, Del Coz Díaz JJ, Lopez-Quijada L. Flexible systems anchored to the ground for slope stabilisation: Critical review of existing design methods. Eng Geol 2011;122(3–4):129–45. doi: https://doi.org/10.1016/j.enggeo.2011.05.014.

[3] Justo JL, Castro D, Azañón JM, Saura J, Durand P, Romero E, et al. Environmental and mechanical aspects of an anchored mesh for stabilisation of a cliff at La Alhambra. B Eng Geol Environ 2014;73(2):667–85. doi: https://doi.org/10.1007/s10064-013-0507-2.

[4] Megal LML. High capacity reinforced flexible systems for slope stabilization: An outstanding technology, not well known (2013) Geotechnical Special Publication, (231 GSP), pp. 1701-1710.

[5] Sasiharan N, Muhunthan B, Badger TC, Shu S, Carradine DM. Numerical analysis of the performance of wire mesh and cable net rockfall protection systems. Eng Geol 2006;88(1–2):121–32. doi: https://doi.org/10.1016/j.enggeo.2006.09.005.

[6] Giacchetti, G., Grimod, A. Rockfall mitigation using simple drapery system: Design approach (2015) Engineering Geology for Society and Territory - Volume 2: Landslide Processes, pp. 1881-1884. https://doi.org/10.1007/978-3-319-09057-3_333

[7] Thoeni K, Lambert C, Giacomini A, Sloan SW. Discrete modelling of hexagonal wire meshes with a stochastically distorted contact model. Comput Geotech 2013;49:158–69. doi: https://doi.org/10.1016/j.compgeo.2012.10.014.

[8] Blanco-Fernandez E. Sistemas flexibles de alta resistencia para la estabilización de taludes. Revisión de los métodos de diseño existentes y propuesta de una nueva metodología de dimensionamiento. Santander: Universidad de Cantabria; 2011 [Ph.D. thesis].

[9] Torres-Machi C, Nasir F, Achebe J, Saari R, Tighe SL. Sustainability Evaluation of Pavement Technologies through Multicriteria Decision Techniques. J Infrastruct Syst 2019;25(3). https://doi.org/04019023.10.1061/(ASCE)IS.1943-555X.0000504.

[10] Elizondo-Martínez EJ, Andrés-Valeri VC, Rodríguez-Hernández J, Sangi C. Selection of additives and fibers for improving the mechanical and safety properties of porous concrete pavements through multi-criteria decision-making analysis. Sustainability-Basel 2020;12(6):2392. doi: https://doi.org/10.3390/su12062392.

[11] Wang M, Sweetapple C, Fu G, Farmani R, Butler D. A framework to support decision making in the selection of sustainable drainage system design alternatives. J Environ Manage 2017;201:145–52. doi: https://doi.org/10.1016/j.jenvman.2017.06.034.

[12] Jato-Espino D, Castillo-Lopez E, Rodriguez-Hernandez J, Canteras-Jordana JCA. review of application of multi-criteria decision making methods in construction. Automat Constr 2014;45:151–62. doi: https://doi.org/10.1016/j.autcon.2014.05.013.

[13] Talema A, Poesen J, Muys B, Reubens B, Dibaba H, Diels J. Multi-criteria-based Plant Species Selection for Gully and Riverbank Stabilization in a Sub-humid Tropical Area. Land Degrad Dev 2017;28(5):1675–86. doi: https://doi.org/10.1002/ldr.2699.

[14] Wu JY, Huang K, Sungkar M. Remediation of Slope Failure by Compacted Soil-Cement Fill. J Perform Constr Fac 2017;31(4):04017022. doi: https://doi.org/10.1061/(ASCE)CF.1943-5509.0000998.

[15] Jato-Espino D, Blanco-Fernandez E, Carpio-Garcia J, Castro-Fresno D. Decision aid system founded on nonlinear valuation, dispersion-based weighting and correlative aggregation for wire rope selection in slope stability cable nets. Expert Syst Appl 2016;54:148–54. doi: https://doi.org/10.1016/j.eswa.2016.01.023.

[16] Saaty T. The analytic hierarchy process, planning, priority setting, resource allocation. New York: McGraw-Hill; 1980.

[17] Blanco-Fernandez E, Castro-Fresno D, del Coz Diaz JJ, Navarro-Manso A, Alonso-Martinez M. Flexible membranes anchored to the ground for slope stabilisation: Numerical modelling of soil slopes using SPH. Computers Geotechnics 2016;78:1–10. doi: https://doi.org/10.1016/j.compgeo.2016.04.014.

[18] Zavadskas EK, Turskis Z, Antucheviciene J. Optimization of weighted aggregated sum product assessment. Electronics Electrical Eng 2012;122(6):3–6. doi: https://doi.org/10.5755/j01.eee.122.6.1810.

[19] Hwang CL, Yoon K. Multiple attribute decision making: methods and applications. Berlin: Springer; 1981.

[20] Castro-Fresno D, López QL, Bianco-Fernandez E, Zamora-Barraza D. Design and evaluation of two laboratory tests for the nets of a flexible anchored slope stabilization system. Geotech Test J 2009;32(4):315–24. doi: https://doi.org/10.1520/GTJ101218.

[21] EN 13253:2016 Geotextiles and geotextile-related products - Characteristics required for use in erosion control works (coastal protection, bank revetments)

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