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UNIVERSITÀ DEGLI STUDI DI TORINO

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1 **Debris flow hazard mitigation: a simplified**
2 **analytical model for the design of flexible**
3 **barriers**

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11

12

13 **Abstract**

14 A channelized debris flow is usually represented by a mixture of solid particles of various sizes
15 and water flowing along a laterally confined inclined channel-shaped region to an unconfined area
16 where it slows down and spreads out into a flat-shaped mass.

17 The assessment of the mechanical behavior of protection structures upon impact with a flow, as
18 well as the energy associated to it, are necessary for the proper design of such structures which, in
19 densely populated areas, can prevent victims and limit the destructive effects of such a
20 phenomenon.

21 In the present paper, a simplified analysis of the mechanics of the impact of a debris flow is
22 considered in order to estimate the forces that develop on the main structural elements of a
23 deformable retention barrier.

24 For this purpose, a simplified structural model of cable-like retention barriers has been developed -
25 on basis of the equation of equilibrium of wires under large displacement conditions, - and the
26 restraining forces, cable stresses and dissipated energies have been estimated.

27 The results obtained from parametric analyses and full-scale tests have then been analysed and
28 compared with the proposed model.

29

30 **Keywords:** *Debris-flow, Barriers, Cable structure.*

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| | | |
|----|---------------------|--|
| 1 | Nomenclature | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | A | Cross section of a horizontal cable |
| 6 | A_t | Cross section of an equivalent cable representing the |
| 7 | | transversal net |
| 8 | $d(t)$ | Depth of a generic cable measured with respect to the |
| 9 | | upper free surface of the accumulated material |
| 10 | d_{ji} | Relative vertical distance between cables i and j |
| 11 | e | Horizontal distance between the first and the last edge |
| 12 | | of a generic cable, measured normal to the cable |
| 13 | E | Young's modulus of the cable |
| 14 | E_b, E_E | Energy dissipated by the brakes and elastic energy |
| 15 | | stored in the cables, respectively |
| 16 | E_t | Young's modulus of the equivalent transversal cables |
| 17 | | representing the net |
| 18 | $f_b, f_{b,\max}$ | Generic force and maximum allowable force in the |
| 19 | | brake |
| 20 | $h(t)$ | Height of the accumulated material at generic time t |
| 21 | h_B | Total height of the barrier |
| 22 | h_0 | Constant height of the debris flow surge |
| 23 | H | Component along the x direction of the tension force |
| 24 | | along a cable |
| 25 | k, g | Earth pressure and gravity acceleration coefficients |
| 26 | L_i, l_i | Effective length and projected length along the x-axes |
| 27 | | of cable i , respectively |
| 28 | n | Number of horizontal cables in the barrier |
| 29 | p | Constant vertical distance between the horizontal cables |
| 30 | $Q_i(x)$ | Total horizontal load acting along a generic i -th cable |

| | | |
|----|------------------------|--|
| 1 | $q_{c,j}, q_{ic}$ | Horizontal load supported by cable j due to load $q(z_i)$ |
| 2 | | acting on cable i and the horizontal load supported by |
| 3 | | cable i when all the other cables are loaded by $q(z_j)$ |
| 4 | $q_d(x)$ | Horizontal load due to the dynamic pressure on the |
| 5 | | barrier |
| 6 | $q_s(d, x)$ | Horizontal load due to the static pressure on the barrier |
| 7 | | at depth d |
| 8 | $q(z_i, t)$ | Horizontal load, at time t , acting directly on the cable |
| 9 | | located at vertical co-ordinate z_i |
| 10 | $s_b, s_{b,max}$ | Generic displacement and maximum allowable |
| 11 | | displacement in the brake |
| 12 | t | Generic time instant |
| 13 | $r(z_j, z_i)$ | Function defining the horizontal ratio between the |
| 14 | | displacements of cable i and cable j (placed at vertical |
| 15 | | coordinates z_i and z_j , respectively) |
| 16 | $T(x, d)$ | Tension force along a cable (in a point having co- |
| 17 | | ordinate x) placed at the depth d |
| 18 | $u(x)$ | Horizontal displacement of a generic point, with co- |
| 19 | | ordinate x , of the cable (in the y direction, as shown in |
| 20 | | Figure 5) |
| 21 | $\bar{u} = u(x = l/2)$ | maximum displacement of the cable, which occurs at its |
| 22 | | midpoint |
| 23 | V | Components in the y direction of the reaction forces |
| 24 | | acting at the cable edges |
| 25 | v_0 | Arrival velocity of the debris flow |
| 26 | z | Generic vertical co-ordinate of the horizontal cable |
| 27 | z_i | Generic vertical co-ordinate of the i -th horizontal cable |
| 28 | α | Empirical coefficient for dynamic pressure estimation |
| 29 | ρ_d | Mass density of the debris flow |
| 30 | θ | Inclination angle of the slope |
| 31 | Fr | Flow rate of the debris [m^3/s] |

| | | |
|---|----------|---|
| 1 | α | Average inclination of the debris deposition behind the |
| 2 | | barrier |
| 3 | μ | Interface friction coefficient between landslide debris |
| 4 | | and deposited debris |
| 5 | T_f | Duration of impact [s] |
| 6 | | |
| 7 | | |

1. Introduction

Debris flows are rapid mass movements, composed of a mixture of grains, water and air, that develop under the effect of gravitational forces. The amount of energy involved in such phenomena is enormous and their mobility is such that it allows them to propagate for several hundreds of meters without losing their destructive potential. Owing to these characteristics, debris flows have been ascribed as being among the most dangerous and catastrophic of natural events [1]. The above cited phenomenon generally originates from collapses (landslides, erosions, etc.) associated with heavy precipitations due to extreme meteorological events such as heavy rainfall or rapid snowmelt. The characteristics that identify a debris flow are:

- A mixture of water and sediments (including sometimes vegetation debris);
- Unstable and non-uniform flow behaviour;
- High velocity of the mobilized mass and strong impact forces;
- Sudden phenomena of short duration.

Govi et al. [2] found, on the basis of a large number of observations that most of these phenomena generate in small to medium scale hydrological basins (up to 13 km²), around 40% of the observed phenomena develop along channels having a with a steeper slope than 35° and more than 40% of the occurrences have a recurring time of over 50 years. Several classification of these phenomena have been proposed by various authors (Pearson & Costa [3]; Costa [4]; Phillips & Davies [5]; Meunier [6]; Wan & Wang [7]; Coussot & Meunier [8]; Hungr et al. [9]; Takahashi [10]). The study of these phenomena is very difficult due to their short duration and unpredictability, the lack of historical data for a given basin and the complexity of the involved mechanical phenomena. Post event surveys allow some of the depositional features to be identified and provide indications on the maximum flow height. However, they lack information on the development of the phenomena with time. For this purpose, recursive events have been monitored out by several authors (Okuda et al. [11]; Marchi et al. [12]; Hürlimann et al. [13]; Tecca et al. [14]). Most of the studies, which had the aim of determining of the characteristic features of a debris flow, have been carried out in artificial channels, where the main involved variables were measured and others were controlled during the tests (Takahashi [10]; Iverson [15]). However, some uncertainties have

1 remained and other scaled models have been developed to simulate deposition
2 mechanics (Mizumaya and Uehara [16]; Liu et al. [17]; Chau et al. [18];
3 Deganutti et al. [19]; Ghilardi et al. [20]; Major [21]) but also to analyze
4 transportation mechanics and energy dissipation [21]. Iverson [15] demonstrated
5 that the uncertainties and difficulties in the interpretation of the experimental
6 results are due to scale effects and to an incorrect artificial reproduction of natural
7 phenomena.

8 In this work, a simplified structural model, developed by the Authors for the
9 safety assessment of retention barriers against channelized debris flows, is
10 presented and some parametric cases and a full scale test on debris flow barriers is
11 interpreted through the proposed approach. This model has been developed as a
12 simplified and efficient tool that can be used to verify of the supporting cables and
13 foundations of a flexible debris flow barrier.

14 The present analytical and numerical-based approach has a different aim than that
15 of a Finite Element Model (FEM). The numerical approach to the problem using
16 3D FEM is in fact a well-known tool in this context (Ferrero [22]). However,
17 computational experience using FEM modeling for these kinds of structures has
18 shown that a large amount of time is needed for the geometrical setup of the
19 model and several numerical instabilities develop due to the non linearity of the
20 problem. The great effort required by FEM for this kind of problem limits the
21 possibility of investigating different geometrical configurations, load schemes etc.
22 It is in fact suitable to represent a specific configuration but does not allow
23 investigation to be made of the influence of debris flow parameter modification
24 (flow height and velocity, debris density etc.). On the other hand, parametrical
25 analyses are common practice in geotechnical design because the aforementioned
26 reasons. Consequently, the Authors decided to develop a simplified method
27 (which is not yet available to our knowledge) that would allow several
28 parametrical analysis to be performed in a limited time. Parametrical analysis
29 should take into account the physical and mechanical features of debris flow
30 which usually vary during debris development and which are consequently
31 difficult to define in a deterministic way. It should be noted that no consideration
32 has been given to the mechanical and physical behavior of debris flows in this
33 paper. The proposed model involves the input parameters being acquired through
34 a preliminary characterization of the design event. However, if the proposed tool

1 is adopted, the designer will be able to perform sensitivity analysis that will help
2 to quantify the influence of parameter variability.

3 **2. Debris flow mechanics**

4 As already mentioned in the introduction, a detailed description of the complex
5 mechanics of a debris flow is not the scope of this paper. This aspect has been
6 studied by several authors considering the different phases that can be identified
7 the debris flow development: the triggering phase [23], the run out phase (e.g.
8 Hungr and Evans [24]; Pirulli [25], Takahashi [10]) and the deposition phase
9 (Major [21], Vallance [26]). However, for the scope of this work, the most
10 relevant aspect is the run out phase and, in particular, the determination of its
11 velocity, volume and discharge rate, since debris flow impact power is connected
12 to its kinetic energy, and to the energy dissipation effects during motion (Cesca
13 [27]).

14 The velocity of a debris flow during its run out depends on several factors, such
15 as: dip of the slope, the water mixture content, the grain distribution etc.. All these
16 factors determine the relationship between the induced internal stresses and the
17 deformation in relation to the applied external stresses, which is usually known as
18 fluid rheology. Since the debris flow is a multi-phase mixture of different
19 materials, its rheology somewhere falls in between the mechanical elastic
20 behavior of the solid phase and the viscous behaviour of the liquid phase. All
21 these aspects determine the kind of motion regime of the debris, which is mainly
22 ruled by both inertia and viscosity forces. The well-known Bagnold number,
23 determined in one of the pioneer works on debris flow rheology carried out by
24 Bagnold [28], is the ratio between these two components (inertia and stresses due
25 to viscosity) and can be used to identify different motion regimes. Bagnold used
26 the term “macroviscous” to indicate a linear regime that is characterized by small
27 Bagnold numbers, in which the shear stresses behave as in a Newtonian fluid with
28 a corrected viscosity, and the term “grain-inertia” to indicate a regime that is
29 characterized by large Bagnold numbers, in which the stresses are independent of
30 the fluid viscosity but dependent on the square of the shear rate and on the square
31 of the granular-phase concentration.

32 A rheological regime, usually termed “collisional”, which is based on the
33 interaction between particles, during which momentum is exchanged and energy

1 is dissipated because of inelasticity and friction, has recently been defined
2 (Goldhirsch [29], Jenkins and Hanes [30]; Hanes [31]).
3 Armanini et al. [32] have shown how as both regimes can be simultaneously
4 present in a debris flow: the behaviour can be reproduced by the kinetic theory in
5 the proximity of the free surface, where the particle concentration is relatively
6 small, while a layer dominated by frictional contacts can be observed near the
7 static bed.

8 The study of debris flow strains and displacements is conveniently analysed
9 considering three fundamental physical principles: mass, energy and momentum
10 conservation, which lead to the driving equations. The above equations can be
11 solved using several different methods: those based on continuum mechanics (i.e.
12 the heterogeneous real mass is treated as a continuum) have been widely and
13 successfully applied (e.g. Chen and Lee [33]; Denlinger and Iverson [34];
14 McDougall and Hungr [35]).

15 When the debris thickness is far smaller than its extent (measured parallel to the
16 bed), averaged depth Saint Venant equations can be used because the debris
17 composition can reasonably be considered constant in a section, due to the limited
18 height, thus avoiding the necessity of a complete 3-dimensional description of the
19 flow (Savage and Hutter [36]).

20 The design of barriers against debris flows is based on the impact forces that are
21 determined by the sum of the dynamic pressure (which can reach values up to the
22 order of 10 KN/m^2) and of the particle collision (which is characterized by values
23 of 100 KN/m^2 or more) (Suwa and Okuda [37]).

24 The dynamic impact can theoretically be estimated assuming an incompressible
25 fluid hypothesis against a rigid barrier, and can be the assessed on the basis of
26 momentum conservation for a steady fluid motion (Hungr [38]; Van Dine [39])
27 while a theoretical solution for cable-like retention barriers is still not available.

28 **2.1 Forces induced by debris-barrier impact**

29 The pressure produced by the impact of a debris flow on the barrier can be
30 estimated considering both the dynamic impact pressure and the static pressure of
31 the deposited debris (Kwan & Cheung [40]). The former can be determined
32 considering the well-known Bernoulli theorem; the kinetic energy of the flowing
33 material, $\rho_d \cdot v_0^2 / 2$, is in fact into a pressure load when the velocity vanishes due

1 to the impact. The dynamic pressure on the barrier can thus be estimated as (Fig.
2 1a):

$$q_d(x) = \alpha \cdot \rho_d \cdot v_0^2 \quad (1)$$

3 where α is an empirical coefficient that varies between 1.5 and 5, according to
4 Canelli et al. [41] and which can be assumed to be equal to 2.0 when the barrier is
5 flexible and drained, the flow regime is granular and there is a lack of site
6 specific information, where ρ_d, v_0 are the density and the impact velocity of the
7 debris, respectively. Studies have been carried out to back analyze some natural
8 debris flow phenomena that have impacted monitored barriers [42] using a multi-
9 stage surge model. However, some of the parameters involved in the analysis
10 were estimated (i.e. the lateral earth pressure coefficient, the density of the debris,
11 etc.) while others were measured directly (i.e. front velocity, surge height, etc.).
12 An extensive analysis on design approaches for debris resisting barriers has been
13 presented by Kwan & Cheung [40].

14 Generally, the debris could hit the barrier in the form of surges which fill the
15 barrier either continuously or intermittently; the most critical impact scenario on
16 barrier stability should always be chosen [40].

17 The thickness (h_0) and velocity (v_0) of moving debris surges can be estimated
18 from debris mobility models using appropriate rheological parameters such as
19 those recommended by Lo [43]. On the other hand, when the debris starts to
20 accumulate behind the barrier, a static pressure can be assumed to occur (Fig. 1).
21 The height of the accumulated material at the generic time t can be estimated, as
22 shown in Eq. (2), by equating the volume of the material that arrives after such a
23 time interval from the slope and the volume of the accumulated material behind
24 the barrier (Fig. 1), (time $t=0$ is assumed when the first particle of the debris-flow
25 impacts the barrier) as:

$$h(t) = \sqrt{2 \cdot v_0 \cdot t \cdot h_0 \cdot \tan \theta} \quad (2)$$

26 In the above relation h_0, θ are assumed to be the constant height of the debris
27 flow surge and the inclination of the slope behind the barrier, respectively. It
28 should be noted that, in order to use Eq. (2) it is necessary that $\theta > 0$. The static
29 pressure acting at depth $d(t)$, measured with respect to the upper free surface of
30 the material (Fig. 1b), can be assessed through the relation reported in Eq. (3), as

1 usually occurs in geotechnical science for the assessment of the static pressure
 2 produced at a given depth:

$$q_s(d) = k \cdot d(t) \cdot \rho_d \cdot g = k \cdot \underbrace{(h_0 + h(t) - z)}_{d(t)} \cdot \rho_d \cdot g \quad (3)$$

3 where k, g are the earth pressure coefficient and the acceleration of gravity,
 4 respectively, while z is the vertical position of the point under consideration (Fig.
 5 1b).

6 By considering the barrier made up of n horizontal supporting cables -in the
 7 following assumed to be placed at a constant relative distance of
 8 $p = h_B / (n-1)$ for the sake of simplicity the pressure load $q_i(z_i)$ (assumed to be
 9 constant along each horizontal cable) acting on the i -th cable located at the
 10 vertical co-ordinate $z_i = h_B \cdot (i-1) / (n-1) \geq h_0$ can simply be calculated as in Eq.
 11 (4) (the cables are numbered starting from 1 at the bottom of the barrier),

$$q(z_i \geq h_0, t) = \begin{cases} 0 & t < t_1 = (z_i - h_0)^2 / (2v_0 h_0 \operatorname{tg} \theta) \\ q_d = \alpha \cdot \rho_d \cdot v_0^2 & t_1 \leq t \leq t_2 = z_i^2 / (2v_0 h_0 \operatorname{tg} \theta) \\ q_s = k \cdot \left[h_0 + h(t) - h_B \cdot \frac{(i-1)}{(n-1)} \right] \cdot \rho_d \cdot g & t > t_2 \end{cases} \quad (4)$$

12 while Eq. (5) should be used when the i -th cable is located at vertical coordinate
 13 $z_i < h_0$

$$q(z_i < h_0, t) = \begin{cases} q_d = \alpha \cdot \rho_d \cdot v_0^2 & t < t_1 = z_i^2 / (2v_0 h_0 \operatorname{tg} \theta) \\ q_s = k \cdot \left[h_0 + h(t) - h_B \cdot \frac{(i-1)}{(n-1)} \right] \cdot \rho_d \cdot g & t \geq t_1 \end{cases} \quad (5)$$

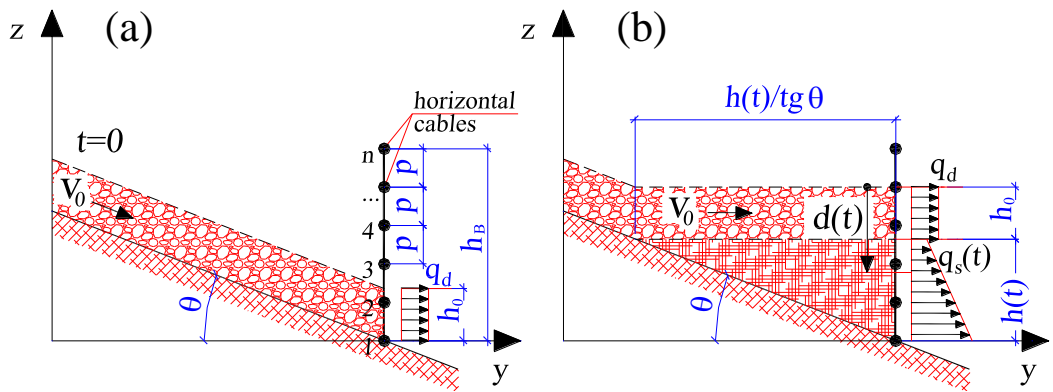
14 In others words, Eqs (4) and (5) enable one to evaluate the pressure exerted
 15 directly on a given cable located at coordinate z_i , once its position with respect to
 16 the flowing material and to the accumulated material is known. Eq. (4) is valid for
 17 cables located at a greater height than the thickness of the flowing debris at
 18 different time intervals: the cable is not yet in contact with the debris material for
 19 $t < t_1 = (z_i - h_0)^2 / (2v_0 h_0 \operatorname{tg} \theta)$ and it is therefore unloaded; for the
 20 $t_1 \leq t \leq t_2 = z_i^2 / (2v_0 h_0 \operatorname{tg} \theta)$ interval the i -th cable falls inside the portion of the
 21 barrier that impacts with the flowing debris while the cable for $t > t_2$ is in contact
 22 with the material at rest behind the barriers. Similarly, Eq. (5) allows one to

1 estimate the pressure on a cable located at a coordinate z_i which is lower than the
 2 thickness of the flowing material.
 3 Since the cables are placed at a constant vertical distance of p , the distributed
 4 load (assumed, for the sake of simplicity to act in a horizontal plane) acting on a
 5 single cable of unit horizontal length is given by Eq. (6)

$$q_i(z_i, t) = q_i(d, t) = \begin{cases} p \cdot q(z_i, t) / 2 & i = 1, n \\ p \cdot q(z_i, t) & 2 \leq i \leq n-1 \end{cases} \quad (6)$$

6 The above and following relations are obviously not restricted by the hypothesis
 7 of a constant p . More general relationships can be obtained for variable relative
 8 cable distances. However, for the sake of analytical simplicity, such a hypothesis
 9 has been introduced to illustrate the analytical model.

10 While calculating the pressure acting on the barrier, the model does not take into
 11 account the deformation induced by the pressure exerted by the flowing granular
 12 material; since the case of a rigid barrier is the most critical in the design of such
 13 retention structures, the mitigation of the pressure, due to the barrier deformation,
 14 can reasonably be neglected from the safety point of view. This hypothesis holds
 15 true since the maximum transversal displacement of the barrier, as inferred from
 16 both experimental and numerical results, is usually much lower (10 - 15%) than
 17 the barrier extension (see Par. 4.2).



18

19 *Fig. 1. Debris accumulation behind the barrier and corresponding loads at a*
 20 *generic time instant.*

21

22 The assumption of a constant load along the cable is an acceptable simplification
 23 from the engineering safety point of view; this hypothesis allows one to treat the
 24 problem as a two dimensional one, characterised by governing equations that can

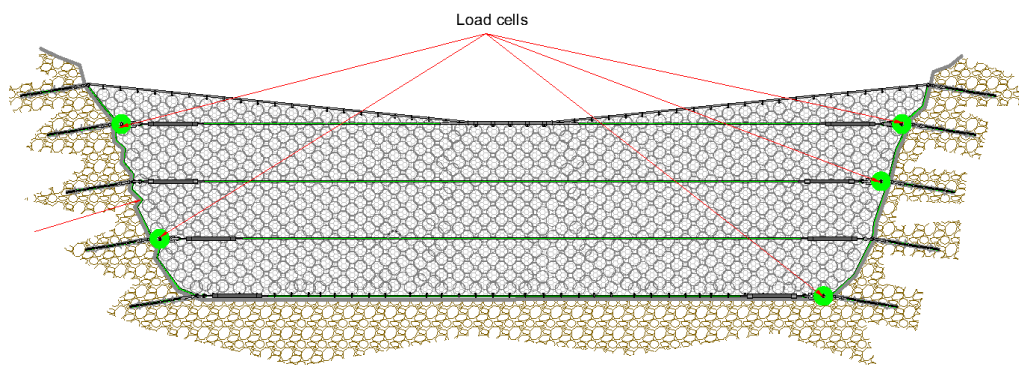
1 easily be handled for a simplified design of the retention barrier, as will be shown
2 hereafter.

3

4 **3. Mechanics of cable-like retention barriers**

5 A simplified structural model for the assessment of the forces that develop in the
6 retention barrier against a channelized debris flow can be formulated taking into
7 account the typical structural lay-out of such elements.

8 The typical channelized debris flow barrier has an almost trapezoidal shape and is
9 anchored to the ground (generally at the channel sides) by means of grouted
10 anchors or cables. The main structural cables are horizontal and their number
11 depends on the overall height and on the expected flow parameters (Fig. 2).



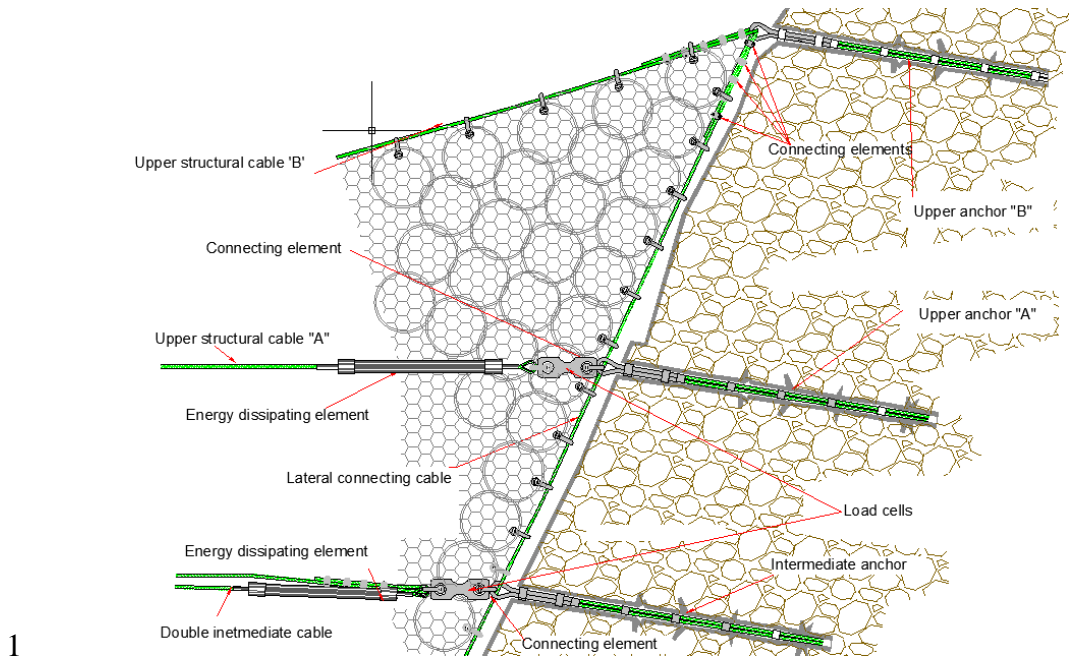
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13 *Fig. 2. Typical structural lay-out of a net retention barrier against debris-flow.*
14 *The single element features and the geometrical lay-out can vary according to the*
15 *make and model of the barrier and to particular installation conditions (channel*
16 *size, depth, etc.). The load cells referred to here are those that were used during*
17 *on site tests carried out at the Pieve di Alpago (BL, Italy) test site (see Section 4).*

18

19 To each horizontal cable can be connected a dissipating element that would limit
20 the amount of force transferred to its foundations during the debris flow impact
21 (Fig. 3).

22 The structural net is typically formed by interconnected steel rings of
23 homogeneous diameter (typically 30-50 cm); sometimes another net with smaller
24 diameter openings is overlaid to the first one to retain smaller debris particles.



1
2 *Fig. 3. Particular of the barrier foundations, dissipating elements and supporting*
3 *cables. Single elements are variable with the make and model of the barriers*
4 *available on the market.*



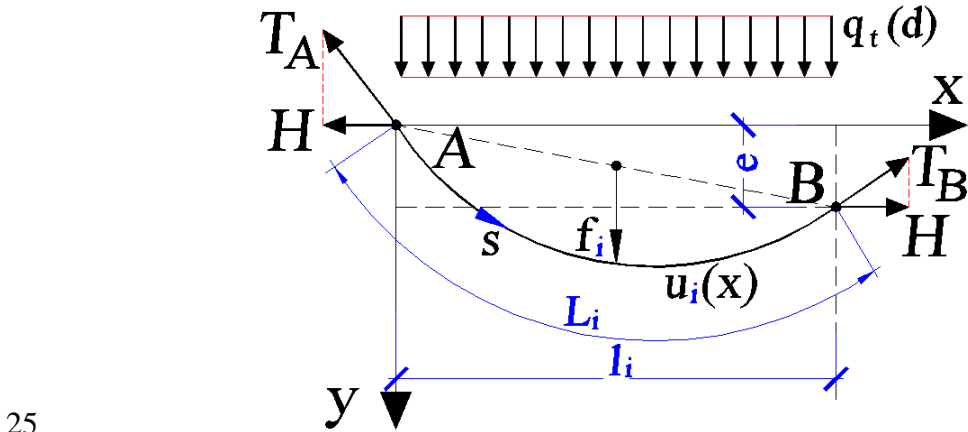
6
7 *Fig. 4. Example of a debris flow barrier (installed at the Pieve di Alpago (BL,*
8 *Italy) test site, see Section 4).*

9
10 From the observation of Fig. 2 it can be noted that the main resisting elements are
11 the horizontal cables fixed at their extremities to the foundations, while the net has

1 the role to retain the flowing solid particles and to transmit the developed forces to
 2 the above described cables.
 3 The governing equation of the equilibrium of a loaded cable can be usefully
 4 employed to describe the mechanical behaviour of such a structural system.
 5 Let us consider the barrier constituted by several horizontal cables mounted at a
 6 reciprocal constant distance equal to p . The i -th cable - having its extremities
 7 fixed at the points A and B - is characterized by a horizontal length equal to l_i ,
 8 while its total effective length (when elongated under loading) is assumed to be
 9 equal to L_i (Fig. 5). The distributed load acting on such a cable is assumed to lie
 10 in an horizontal plane and to be constant with respect to the x co-ordinate at a
 11 fixed time t . The load is, however, variable with time, since the depth $d(t)$ of the
 12 cable with respect to the top surface of the flowing material increases with t (Fig.
 13 1b).
 14

15 3.1. Formulation of the equilibrium equation of a cable-like structure

16 The present model, for sake of simplicity, considers the main resisting cables to
 17 be loaded only in the horizontal direction by the forces produced by the debris
 18 impact on the barrier, while the resultant of the vertical forces transmitted by the
 19 connecting net to the single cable is considered as negligible. As a consequence,
 20 only the deformation of the cables in the horizontal plane will be assumed to be
 21 significant in the resistant mechanism of the structure.
 22 Each cable of the barrier is assumed to have fixed extremities, i.e. the end points
 23 of the cables are prevented to displace by some foundation system which
 24 mechanical behavior is beyond the scope of the present research.



1 *Fig. 5. Scheme of the top view of a single cable under the forces produced by the*
 2 *impact of a debris-flow, with related geometrical and static quantities.*

3

4 Starting from the equilibrium equation (Eq.(7)) of the i -th cable in differential
 5 form at the time instant t [44],

$$\frac{d^2 u_i(t)}{dx^2} = -\frac{q(z_i, t)}{H_i} = -\frac{q_i(d, t)}{H_i} \quad (7)$$

6 after a double integration and by assuming a constant distributed load at a given
 7 time instant $q_i(d)$ (the dependence on time t for sake of brevity is not explicitly
 8 indicated in the following relations) and the two extremities of the cable to be
 9 located at the coordinates $(x, y) = (0, 0)$ and $(x, y) = (l_i, e)$ (referred to the
 10 horizontal plane containing the cable, Fig. 5) corresponding to the points A and B,
 11 respectively, the cable equation can be explicitly written as (Levy [45]):

$$u_i(x) = \frac{q_i(d)}{2H_i} (x \cdot l_i - x^2) + \frac{e}{l_i} x \quad (8)$$

12 where $q_i(d) = q(z_i = h_b - d)$ is the constant horizontal load acting along the cable
 13 under consideration placed at a depth d below the actual top free surface of the
 14 flowing material, while H_i is the constant component along the x direction of the
 15 tensile axial force $T_i(x)$ in the cable [44]. Such a quantity can be obtained by
 16 imposing the effective length of the cable to be equal to L_i through the equation:

$$L_i = \int_0^{l_i} \sqrt{1 + u_i'^2(x)} dx \quad (9)$$

17 which is obtained by integrating the trivial geometric relation

18 $dL_i = \sqrt{dx^2 + dy^2} = dx \sqrt{1 + u_i'^2(x)}$ (since $dy = dx \cdot u_i'(x)$) that quantifies the
 19 length of a generic curve which shape is described through the displacement
 20 relation $u_i(x)$.

21 By denoting with f the quantity $f = q_{ii} \cdot l_i^2 / 8H_i$ (see Fig. 5, where the
 22 geometrical interpretation of f is represented, i.e. the maximum transversal
 23 displacement measured with respect to the straight line A-B) and expanding in

1 Taylor series the expression of the integrand function in Eq. (9) (the dependence
2 on the depth d is omitted in the notation for simplicity), one can obtain:

$$L_i \cong l_i \cdot \left(1 + \frac{8}{3} \frac{f^2}{l_i^2} + \frac{1}{2} \frac{e^2}{l_i^2} \right) + \dots \quad (10)$$

3 The sought term H_i , which can be demonstrated from equilibrium considerations
4 to be independent of x , can be finally obtained by using Eqs (8-10):

$$H_i \cong \frac{\sqrt{3}}{6} \cdot \frac{q_i \cdot l_i^2}{\sqrt{2L_i \cdot l_i - 2l_i^2}} \quad (11)$$

5 where the particular case characterised by $e = 0$, has been considered.

6 The tensile force $T_i(x)$ acting along the cable can be also explicitly obtained
7 through the following relation (Levy [45]):

$$T_i(x) = H_i \cdot \frac{ds}{dx} = H_i \cdot \sqrt{1 + u_i'^2(x)} = H_i \cdot \sqrt{1 + \left[\frac{q_i}{2H_i} (l_i - 2x) \right]^2} \quad (12)$$

8 by projecting the force H_i along the tangential direction of the cable in the point
9 of interest or, in other words, by calculating the product $H_i \cdot ds/dx$, where s
10 denotes the curvilinear abscissa along the cable under consideration (Fig. 5).
11 At the two extremities of the cable, the components of the reaction forces in the y
12 direction are given by the trivial value:

$$V_i(x=0) = V_i(x=l_i) = H_i \cdot \frac{du_i}{dx} \Big|_{x=0}^{x=l_i} = \frac{q_i \cdot l_i}{2} \quad (13)$$

13 The elastic deformation of the cables under loading must be also considered in
14 order to explicitly write the total effective length L_i ; in such a case the problem is
15 characterised by another source of nonlinearity due to the dependence of the cable
16 length L_i on the tensile force $T_i(x)$ which depends itself on L_i .

17 Under limited deformation – 10-15% of the cable length - it can be assumed that
18 the tensile force $T_i(x)$ is approximately equal to H_i (which does not depend on x)
19 all along the cable, i.e. $T_i(x) \cong H_i = const.$ (since $ds \cong dx$); in such a way the
20 effective length of the cable (assumed to obey the linear elastic Hooke's law) L_i
21 can be written as:

$$L_i = l_i \cdot \left(1 + \frac{H_i}{E_i A_i} \right) \quad (14)$$

1 The limited deformation of each cable is considered in order to maintain the
2 appropriate functionality of the structure. According to Kwan & Cheung [40] the
3 deformable barrier should sustain structural integrity for a deformation in the
4 direction of the debris impact not lower than 10% of its total length and, in order
5 to retain a considerable amount of material behind its deformed shape, it is
6 suggested that the final deformation should not be greater than 15% of its total
7 length.

8 The last relation used together with Eq. (11) allows to calculate – by solving the
9 obtained non-linear problem – the effective cable length and the corresponding
10 force H_i at the equilibrium state. The above assumption can be justified by
11 considering that even for a cable having a noticeable transversal deformation
12 such as $f = 0.1 \cdot l_i$, its effective length is $L_i \cong 1.027 \cdot l_i$ (see Eq. (10)) and the axial
13 force value along the cable lies in the range $H_i \leq T_i(x) \leq 1.08 \cdot H_i$ (obtained by
14 using Eqs (11) and (13)), while for $f = 0.2 \cdot l_i$, $L_i \cong 1.107 \cdot l_i$ and
15 $H_i \leq T_i(x) \leq 1.28 \cdot H_i$. It must be also recalled that, in debris flow net barriers, the
16 presence of brakes is quite common; such a devices operate by dissipating energy
17 and by increasing the cable length once the maximum allowable force of the brake
18 is reached. Such an increased length produces a beneficial effect by inducing a
19 decrease of the tension forces in the cables, while neglecting the brakes usually
20 leads to a conservative design of the barriers. Such a topic will be discussed in
21 Sect. 3.3 where the brakes modelling is presented.

22 The maximum displacement of the i -th cable occurring at its midpoint in the
23 particular case $e = 0$, is equal to $\bar{u}_i = u_i(x = l_i/2) = q_i \cdot l_i^2 / 8H_i$ (see Eq. (8)). The
24 relation between the distributed load q_i and such a maximum displacement can
25 thus be written from the solution of the equations below:

$$q_i(\bar{u}_i) = \frac{8H_i \cdot \bar{u}_i}{l_i^2} \quad (15)$$

$$\text{with } H_i \cong \frac{\sqrt{3}}{6} \cdot \frac{q_i \cdot l_i}{\sqrt{2} \sqrt{\left(1 + \frac{H_i}{E_i A_i}\right) - 1}} \rightarrow H_i = \left(\frac{q_i^2 \cdot l_i^2 \cdot E_i A_i}{24} \right)^{1/3}$$

1 where the relation for the approximate cable effective length evaluation (Eq. 14),
 2 has been used together with Eq. (11); finally the sought relation $q_i(\bar{u}_i)$ (see Eq.
 3 (15₁)) can be explicitly obtained:

$$q_i(\bar{u}_i) = \frac{64 E_i A_i}{3 l_i^4} \cdot \bar{u}_i^3 \quad (16)$$

4

5 **3.2. Effect of the net connections between cables**

6 Since the horizontal cables are connected by the barrier net, it can be assumed that
 7 they are joined together by ‘equivalent’ vertical cables having the effect to
 8 distribute a portion of the load directly applied to each horizontal cable to the
 9 adjacent ones (Fig. 6a). The differential equilibrium equation Eq. (7) for the i -th
 10 horizontal cable can thus be modified as:

$$\frac{d^2 u_i}{dx^2} = - \frac{q_i(x) - q_{ic}(x) + q_{ci}(x)}{H_i} = - \frac{Q_i(x)}{H_i} \quad (17)$$

11 in which $q_{ic}(x), q_{ci}(x)$ represent the portion of the “direct” load $q_i(x)$ acting on
 12 cable i transferred to the adjacent cables and the “indirect” loads transmitted to the
 13 cable i from the other loaded cables, respectively, i.e.:

$$q_{ic}(x) = \sum_{\substack{j=1 \\ j \neq i}}^n q_{i,j}(x), \quad q_{ci}(x) = \sum_{\substack{j=1 \\ j \neq i}}^n q_{j,i}(x) \quad (18)$$

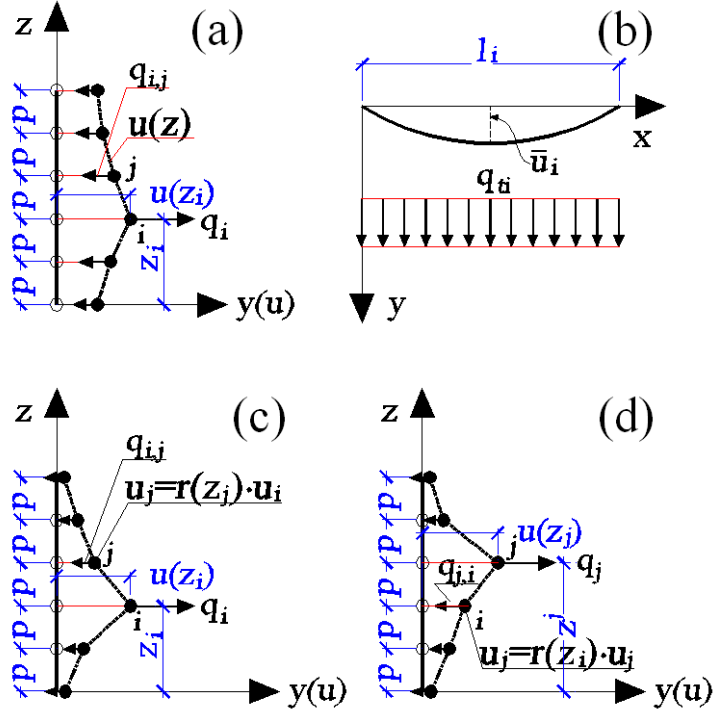
14 where $q_{i,j}(x)$ is the “indirect” load carried by the cable j when the “direct” load
 15 $q_i(x)$ is acting on the cable i , while $q_{j,i}(x)$ is the “indirect” load carried by the
 16 cable i when the “direct” load $q_j(x)$ is acting on the cable j .

17 In other words, the load $q_{ic}(x)$ represents the total fraction of the “direct” load
 18 acting on the cable i carried by all the other cables $j \neq i$, while $q_{ci}(x)$ represents
 19 the sum of the portions of the “direct” loads acting on all the other cables $j \neq i$
 20 transferred to the cable i .

1 As previously stated, for sake of simplicity, it can be assumed the loads
2 $q_i(x), q_{ic}(x)$ and $q_{ci}(x)$ to be constant along the x -coordinate and acting on the
3 horizontal plane containing each cable. The problem is now to estimate the loads
4 $q_{i,j}$ and $q_{j,i}$ in order to rewrite the equilibrium condition, given by Eq. (17), with
5 the proper effective total transversal load $(q_i - q_{ic} + q_{ci})$. Due to the load-
6 maximum deflection relationship given by Eq. (16), the loads $q_{i,j}$ and $q_{j,i}$ in Eq.
7 (18) can be evaluated once the maximum displacement $\bar{u}_{i,j}$ of the cable j
8 (produced by the distributed load q_i acting on cable i , Fig. 6a, c) or the maximum
9 displacement $\bar{u}_{j,i}$ of the cable i (produced by the load q_j acting on cable j , Fig.
10 6d) are known.

11 It should be recalled that, in the real case, the cables in the barrier are not only
12 subjected to horizontal loads but also to vertical ones due to the effect of the
13 transversal net connecting them (see Figs 2-4). In a general case, by considering a
14 distributed load acting on a single inclined plane along the whole cable, the
15 deflection of a single wire takes place in a plane containing the cable extremities
16 and the load direction, i.e. the present model can still be applied but in a different
17 plane from the horizontal one.

18 It must be also considered as the vertical components of the forces acting along a
19 single cable are significant only for the uppermost one, since the lower and the
20 intermediate cables of the barrier are usually either restrained by the channel
21 bottom or symmetrically surrounded by other cables, with the consequence of
22 being subjected to a simple nearly horizontal force.



1

2 *Fig. 6. Scheme of the forces developed in cables j for a load acting on the cable i*
 3 *(a); horizontal cable under a concentrated load (b); simplified model for the*
 4 *assessment of the load carried by the cables adjacent to cable i for a load q_i*
 5 *acting on it (c, d).*

6

7 By indicating with $\bar{u}_{i,j}$ the maximum displacement occurring in cable j when the
 8 cable i shows a maximum displacement equal to \bar{u}_i , an influence function
 9 $0 \leq r(z_j, z_i) \leq 1$ (Fig. 6c, d) can be written in order to correlate the above
 10 quantities as,

$$\bar{u}_{i,j} = r(z_j, z_i) \cdot \bar{u}_i \quad (19a)$$

11 the value of the distributed “indirect” load acting along the generic cable j
 12 transmitted from the cable i can be expressed as:

$$q_{i,j} = q_i \cdot \frac{r^3(z_j, z_i) \cdot C_j}{\sum_{k=1}^n r^3(z_k, z_i) \cdot C_k} \quad \text{with} \quad C_j = \frac{64 \cdot E_j A_j}{3l_j^4} \quad (19b)$$

13 The above relations can be obtained by writing the equilibrium condition for unit
 14 cable length $\sum_{j=1}^n q_{i,j} = q_i$, and the $n-1$ displacements relationships between the
 15 cable i and the remaining cables $j \neq i$:

$$\bar{u}_i^{-3} = \left[r(z_j, z_i) \cdot \bar{u}_j \right]^3 \quad \text{with} \quad j = 1, 2, 3, \dots, i-1, i+1, \dots, n \quad (20)$$

1 Eq. (20) correlates the value of the maximum displacement of the cable i with
2 respect to the cable j by mean of the function $r(z_j, z_i)$. In other words, the above
3 relations express the maximum deflection of the cable i by using the maximum
4 deflection of the cable j multiplied by the influence function $r(z_j, z_i)$.
5 Therefore, since there exists a direct relation between the distributed load acting
6 on a cable and its maximum displacement (Eq. (16)), the load acting on a generic
7 cable can be obtained once its maximum deflection is known.
8 It can be observed that the function $r(z, z_i)$ is representative of the mechanical
9 properties of the vertical 'equivalent' cables connecting the horizontal ones: in
10 fact, if the net connected to the horizontal cables is very weak, when the cable i is
11 displaced by a certain amount the displacements in the other connected horizontal
12 cables would result as depicted in Figs 6c, d, with a rapid decrease of the
13 displacements values for an increasing vertical distance from the cable i . On the
14 other hand, in the case of a strong connecting net, the displacements of the cables
15 would be as depicted in Fig. 6a, with a lower reduction effect as the vertical
16 distance from the displaced cable i increases.
17 The governing equations (7) can be rewritten, using the above relations, as:

$$\frac{d^2 u_i}{dx^2} = - \frac{q_i - q_{ic} + q_{ci}}{H_i} = - \frac{q_i - \sum_{\substack{j=1 \\ j \neq i}}^n q_{i,j} + \sum_{\substack{j=1 \\ j \neq i}}^n q_{j,i}}{H_i} = \quad (21a)$$

$$= - \frac{\beta_i \cdot q_i \cdot \frac{r^3(z_i, z_i) \cdot C_i}{\sum_{k=1}^n r^3(z_k, z_i) \cdot C_k} + \sum_{\substack{j=1 \\ j \neq i}}^n \beta_j \cdot q_j \cdot \frac{r^3(z_j, z_i) \cdot C_i}{\sum_{k=1}^n r^3(z_k, z_j) \cdot C_k}}{H_i} = - \frac{Q_i}{H_i} \quad (21b)$$

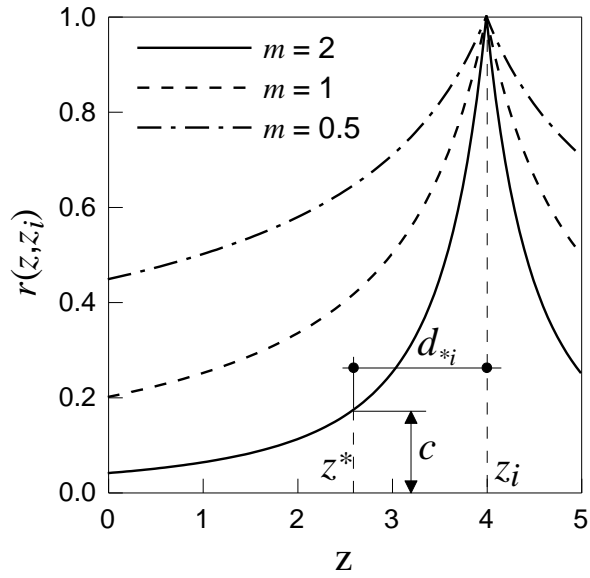
$$\text{with} \quad H_i = \left(\frac{Q_i^2 \cdot l_i^2 \cdot E_i A_i}{24} \right)$$

18 that represents a system of nonlinear second order ordinary differential equations
19 with $\bar{u}_j^{-3} = u_j^3(x = l_j/2)$, $\bar{u}_i^{-3} = u_i^3(x = l_i/2)$ and the coefficient $\beta_j = 1.0$ if $q_j \neq 0$
20 and $\beta_j = 0$ if $q_j = 0$. The last cited coefficient needs to be introduced in order to

1 take into account for the possibility that not all the cables are loaded at the same
2 time.
3 It must be underlined as, in the above equations, any inertial effect is neglected
4 since the mass of the retention barrier is very small and the horizontal acceleration
5 of the cable and of the flowing material in contact with it can be supposed to be
6 low during the whole loading process.
7 The above introduced function $r(z_j, z_i)$ can be reasonably assumed in the form:

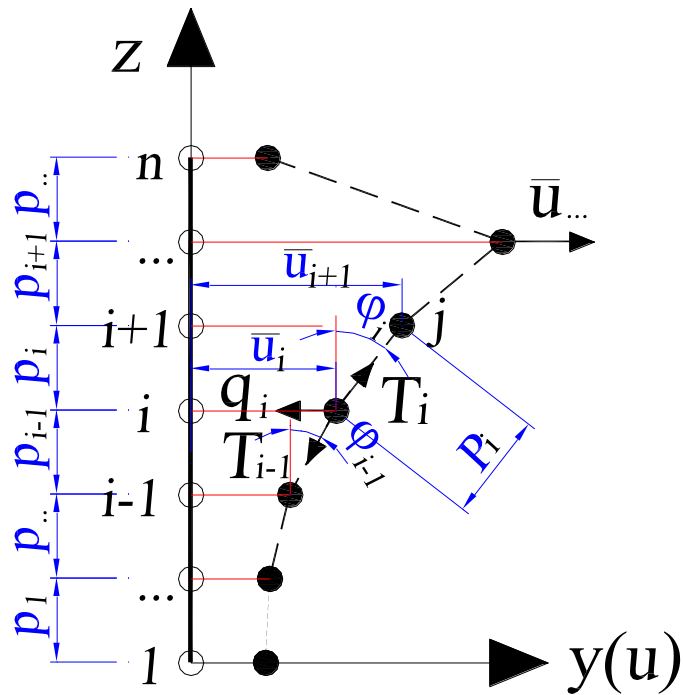
$$r(z_j, z_i) = \frac{1}{\left(|z_j - z_i| + 1\right)^{m_{ji}}} \quad \text{where} \quad m_{ji} = \frac{-\ln(c)}{\ln\left(|z^* - z_i| + 1\right)} \quad (22)$$

8 in which $r(z^*, z_i) = c$ is the value attained by the function $r(z_j, z_i)$ at the vertical
9 coordinate $z_j = z^*$ (i.e. for a cable placed at a relative distance from cable i equal
10 to $d^*_i = |z^* - z_i|$) while the unit value of $r(z_j, z_i)$ is attained at $z_j = z_i$ (Fig. 7).
11 The assumed $r(z_j, z_i)$ indicates that the relation between the displacement of
12 different horizontal cables depends on their relative vertical distance d_{ji} and on
13 their reciprocal position. It can be observed that $m_{ji} \neq m_{ij}$ due to the non-linear
14 force-displacement relationship (see Eqs (16) and (19b₁)). This is due to the
15 difference between the relative displacement arising in cable i when cable j is
16 subjected to a given displacement, and the relative displacements arising in cable j
17 when cable i is subjected to the same displacement.
18 The function $r(z, z_i)$, if properly tuned through its coefficient m_{ij} , can represent
19 the relation between the displacements of two connected cables.
20



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Fig. 7. Assumed pattern of the function $r(z_j, z_i)$ for different values of the exponent m and for $z_i = 4$ in Eq. (22).



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Fig. 8. Scheme of a vertical section of the barrier; the horizontal cables are represented by filled circles.

9 The determination of the function $r(z, z_i)$ can be achieved by considering the
10 mechanical behaviour of the transversal midsection of the barrier (Fig. 8). The

1 equilibrium condition in the horizontal direction for the i -th cable can be written
 2 as:

$$q_i = T_i \sin \varphi_i - T_{i-1} \sin \varphi_{i-1} \quad (23)$$

$$\text{with } \sin \varphi_i = \frac{\bar{u}_i - \bar{u}_{i-1}}{P_i}, \text{ and } P_i = \sqrt{p_i^2 + (\bar{u}_i - \bar{u}_{i-1})^2},$$

$$T_i = A_{ii} \cdot E_{ii} \cdot \varepsilon_i = A_{ii} \cdot E_{ii} \cdot \frac{\overbrace{P_i - p_i}^{\varepsilon_i}}{P_i} = A_{ii} \cdot E_{ii} \cdot \frac{\sqrt{p_i^2 + (\bar{u}_i - \bar{u}_{i-1})^2} - p_i}{P_i}$$

3 where ε_i is the strain in the vertical cable connected to the horizontal cable i .

4 On the other hand the relation between the applied load and the maximum

5 transversal deflection of the cable is given by $q_i = (64 \cdot E_i A_i / 3l_i^4) \cdot \bar{u}_i^3$ (see

6 Eq.(16)). The above equilibrium equations (23) can thus be rewritten as:

$$q_i = \frac{64 E_i A_i}{3l_i^4} \cdot \bar{u}_i^3 = T_i \sin \varphi_i - T_{i-1} \sin \varphi_{i-1} = A_{ii} E_{ii} \cdot \frac{\sqrt{p_i^2 + (\bar{u}_i - \bar{u}_{i-1})^2} - p_i}{P_i} \cdot \frac{\bar{u}_i - \bar{u}_{i-1}}{P_i} - A_{i-1} E_{i-1} \cdot \frac{\sqrt{p_{i-1}^2 + (\bar{u}_{i-1} - \bar{u}_{i-2})^2} - p_{i-1}}{P_{i-1}} \cdot \frac{\bar{u}_{i-1} - \bar{u}_{i-2}}{P_{i-1}} \quad (24)$$

7 Eq. (24) simply states the equilibrium of the load acting on the cable under study
 8 and those deriving from the other connected cables, expressed by means of their
 9 maximum horizontal displacements.

10 Once the maximum transversal deflection \bar{u}_k of the k -th cable is known, the
 11 maximum transversal deflections of the other cables can be obtained by the
 12 solution of the system of nonlinear equations (see Eq. (24)).

13 The solution of such a system is very awkward and does not allow an easy
 14 analytical treatment to get sought values. For such a reason the determination of
 15 the solution can be obtained through a numerical method; in the present paper an
 16 iterative evolutionary algorithm belonging to the Genetic Algorithm (GA)
 17 approaches is applied (Goldberg [46]; Gen and Cheng [47]).

18 In many physical problems, the solution of their mathematical formulation is often
 19 quite difficult to be determined by applying classical approaches. An increasing
 20 interest in a class of algorithms known as Genetic Algorithms (GAs), which
 21 operate by simulating the natural evolutionary processes of life - the Darwinian
 22 survival of the fittest principle is applied by iteratively improving the current

1 solution [46], [47], has been observed during last decades. Such algorithms
 2 represent random stochastic methods of global optimisation, and are used to
 3 minimise or maximise a chosen objective function suitable for a given problem.
 4 Genetic algorithms have successfully been applied to analyse several problems
 5 such as structural performance optimisation (Gantovnik et al. [48]; Brighenti [49];
 6 Brighenti et al. [50]) and material design and parameters identification (Zohdi
 7 [51]) as well as several non-structural problems.
 8 By using the above cited biological-based algorithm approach, the fulfilment of
 9 some conditions related to a desired objective function can be approximately
 10 imposed; in the present case the objective function to be minimised can be
 11 assumed to be represented by the total error e_{tot} in satisfying the equilibrium
 12 equations of the system (24), i.e.: $e_{tot} = \min$

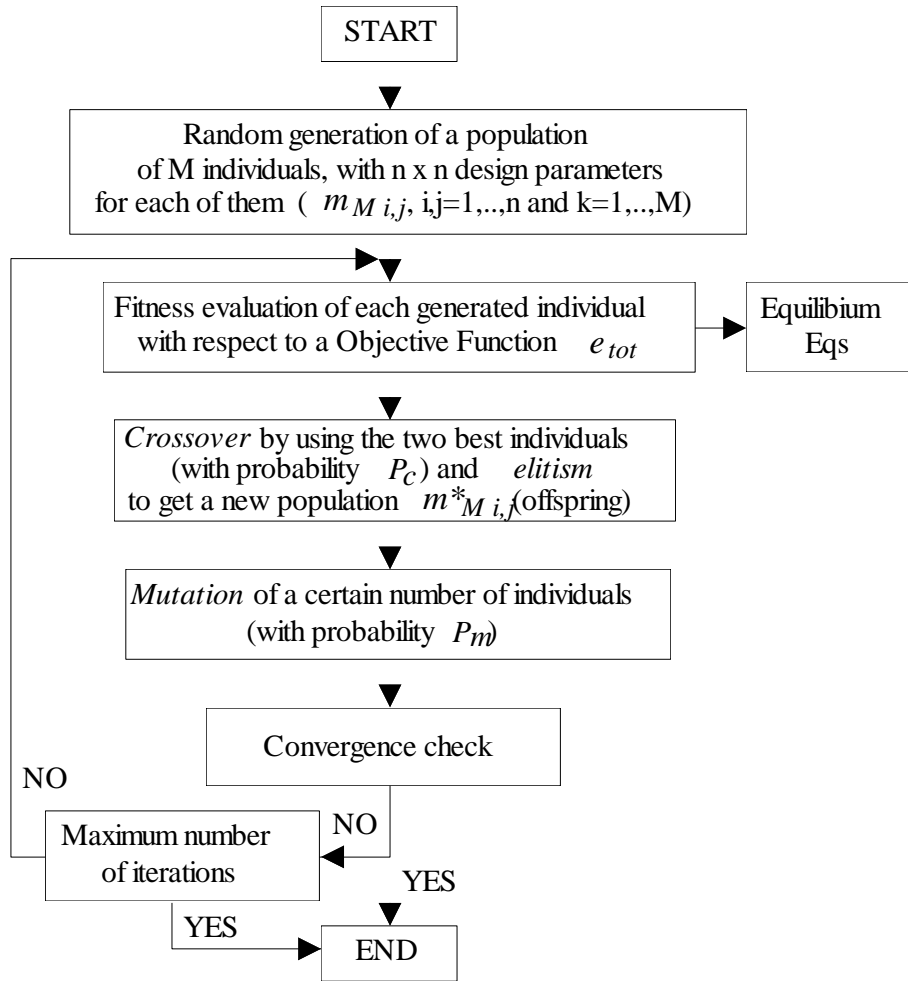
$$e_{tot} = \sum_{i=1}^n |e_i| \quad \text{with} \quad (25)$$

$$e_i = \frac{64E_i A_i}{3l_i^4} \cdot \bar{u}_i^3 - A_{ii} E_{ii} \cdot \frac{\sqrt{p_i^2 + (\bar{u}_i - \bar{u}_{i-1})^2} - p_i}{p_i} \cdot \frac{\bar{u}_i - \bar{u}_{i-1}}{P_i} +$$

$$+ A_{i-1} E_{i-1} \cdot \frac{\sqrt{p_{i-1}^2 + (\bar{u}_{i-1} - \bar{u}_{i-2})^2} - p_{i-1}}{p_{i-1}} \cdot \frac{\bar{u}_{i-1} - \bar{u}_{i-2}}{P_{i-1}}$$

13 In Fig. 9 the flow-chart of the developed Genetic Algorithm used to minimize the
 14 errors expressed by Eq. (25) is reported. As can be observed, several initial
 15 random generations of the sought solution represented by the exponents m_{ij} are
 16 required (initial population made of M individuals). Performing the fitness
 17 evaluation of each individual (quantified through the violation of the equilibrium
 18 equations measured by e_{tot}), the highest ranking results can be identified and used
 19 for subsequent crossover and mutation operations to be carried out in order to get
 20 a new offspring of new individuals to be treated again as the previous one
 21 (Brighenti [49]; Brighenti et al. [50]). By repeating the above process, in an
 22 iterative way, up to the fulfillment of a given error tolerance, the numerical
 23 solution tends to the true solution of the problem.

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Fig. 9. Flow chart of the Genetic Algorithm used for the solution of the system given by Eqs (25).

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As an example, the solution obtained by the GA in the case of 11 equally spaced cables having the same mechanical properties (cross section area, Young modulus and equal length) in which the sixth cable is displaced by a unit quantity ($\bar{u}_5 = 1$) is shown in Fig. 10.

9

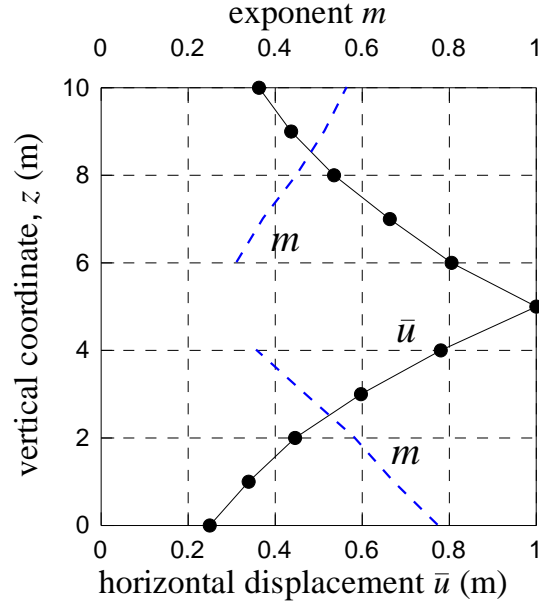
10

It can be observed as the deformed pattern, obtained through the GA approach, is reasonably correct and that the corresponding exponent m_{j5} of the $r(z_j, z_5)$ law, evaluated for each couple of cables by considering the sixth cable as the reference one, is variable in the range 0.3-0.8 (see dashed line in Fig. 10).

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2 *Fig. 10. Deformed pattern of 10 horizontal identical cables, joined by vertical*
 3 *cables, obtained through the GA; the corresponding exponent m of the $r(z_j, z_5)$*
 4 *law (Eq. (22)) is also reported (dashed line).*

5

6 It can be observed as the particular case of totally independent cables can be
 7 simulated by assuming $m_{ji} \rightarrow \infty$ in the expression of $r(z_j, z_i)$ (Eq. (22)); in such
 8 a particular case the differential equations become uncoupled and can be written
 9 as:

$$\frac{d^2 u_i}{dx^2} = -\frac{q_i}{H_i} \quad i = 1, 2, \dots, n, \quad (26)$$

with boundary conditions $u_i(0) = u_i(l_i) = 0$ and $L_i = \int_0^{l_i} \sqrt{1 + u_i'^2(x)} dx$

10

11 Finally, since the solutions of the equilibrium equations given by Eq. (8) can be
 12 observed to be characterised by the same patterns scaled by the value of the
 13 applied uniform load, the above Eqs (21) can be written by considering only the
 14 central maximum displacement for each cable, i.e.

$$\bar{u}_i = u_i(l_i/2) = \frac{\beta_i \cdot q_i \cdot \frac{r^3(z_i, z_i) \cdot C_i}{\sum_{k=1}^n r^3(z_k, z_i) \cdot C_k} + \sum_{\substack{j=1 \\ j \neq i}}^n \beta_j \cdot q_j \cdot \frac{r^3(z_j, z_i) \cdot C_i}{\sum_{k=1}^n r^3(z_k, z_j) \cdot C_k}}{2H_i} \cdot \frac{l^2}{4} = \frac{Q_i \cdot l_i^2}{8H_i} \quad (27)$$

1 In other words, the system of cables is assumed to be governed by n independent
2 variables, \bar{u}_i , that is to say that every cable is completely described by one single
3 parameter (degree of freedom) corresponding to its central and maximum
4 horizontal displacement \bar{u}_i .
5 As a representative example, at the generic time instant t at which we assume to
6 have $q_{t1}(t) \neq 0$, $q_{t2}(t) \neq 0$, $q_{t3}(t) \neq 0$, while $q_{t4}(t) = q_{t5}(t) = \dots = q_{tm}(t) = 0$, in the
7 case of cables having equal length l , cross section area A and elastic modulus
8 E , the system of governing nonlinear equations becomes:

$$\left\{ \begin{array}{l} \frac{8}{l^2} \bar{u}_1 = \frac{q_1}{H_1} \sum_{\substack{j=1 \\ j \neq 1}}^3 \frac{C_1^3 r^3(z_1, z_j)}{D_1} + \frac{C_1}{H_1} \sum_{\substack{j=1 \\ j \neq 1}}^3 \frac{q_j \cdot r^3(z_1, z_j)}{D_j} \\ \frac{8}{l^2} \bar{u}_2 = \frac{q_2}{H_2} \sum_{\substack{j=1 \\ j \neq 2}}^3 \frac{C_2^3 r^3(z_2, z_j)}{D_2} + \frac{C_2}{H_2} \sum_{\substack{j=1 \\ j \neq 2}}^3 \frac{q_j \cdot r^3(z_2, z_j)}{D_j} \\ \frac{8}{l^2} \bar{u}_3 = \frac{q_3}{H_3} \sum_{\substack{j=1 \\ j \neq 3}}^3 \frac{C_3^3 r^3(z_3, z_j)}{D_3} + \frac{C_3}{H_3} \sum_{\substack{j=1 \\ j \neq 3}}^3 \frac{q_j \cdot r^3(z_3, z_j)}{D_j} \\ \frac{8}{l^2} \bar{u}_4 = \frac{C_4}{H_4} \sum_{\substack{j=1 \\ j \neq 4}}^3 \frac{q_j \cdot r^3(z_4, z_j)}{D_j} \\ \dots \\ \frac{8}{l^2} \bar{u}_n = \frac{C_n}{H_n} \sum_{\substack{j=1 \\ j \neq n}}^3 \frac{q_j \cdot r^3(z_n, z_j)}{D_j} \end{array} \right. \quad \begin{array}{l} \text{with } C_i = \frac{64 \cdot EA}{3l^2 H_i}, \\ H_i = \left(\frac{Q_i^2 \cdot l^2 EA}{24} \right)^{1/3}, \\ D_j = \sum_{k=1}^n r^3(z_k, z_j) \cdot C_k \end{array} \quad (28)$$

9 The solution vector \mathbf{u} of the above system contains the maximum displacements
10 of the cables, i.e. $\mathbf{u}^T = \{\bar{u}_1 \quad \bar{u}_2 \quad \bar{u}_3 \quad \bar{u}_4 \quad \dots \quad \bar{u}_n\}$ at the time instant t at which
11 the acting loads are considered.
12 The resulting system of non-linear differential equations (25) can be observed to
13 be characterised by decoupled equations, since the effective coupling between the
14 horizontal displacement is approximately accounted for by the relation given by
15 Eq. (19a) which must be assessed from the value of the exponent m .
16
17 The above described mechanical model has been implemented in a simple in-
18 house made Fortran code operating in two phases: i) determination of the
19 function $r(z_j, z_i)$ (defined through the exponents m_{ij}) by the knowledge of the
20 mechanical and geometrical characteristics of the horizontal cables and of the
21 ‘equivalent’ vertical ones (representing the net) by using the Genetic Algorithm;
22 ii) assessment of the displacements and forces in the deformed barrier in the time

1 domain (corresponding to the time interval of the debris impact on the structure),
 2 by using Eqs (8, 11, 13) calculated at discrete time intervals into which the total
 3 computation time has been subdivided. Obviously, the second phase of the
 4 calculation requires the evaluation of the external loads acting on the barrier
 5 (through Eqs (1-6)) throughout the entire duration of the debris flow
 6 phenomenon.

8 **3.3. Modelling of the brake devices**

9 As recalled at the beginning of the paper, real barriers are usually provided by
 10 brake system that enables to dissipate energy and to increase the cable length by
 11 allowing a beneficial reduction of the tension in the horizontal cables.
 12 Usually, such devices becomes effective when the maximum tensile brake force is
 13 attained during the loading process; after that, the brake maintains such a
 14 maximum characteristic force and dissipates energy, up to the development of the
 15 maximum brake elongation. Once such maximum brake stroke is reached, the
 16 device loses its function and the force in the cable starts to increase again.
 17 The force-displacement relationship for the brake device placed on the cable i can
 18 be written as:

$$f_b = \begin{cases} T_i \cong H_i & \text{if } T_i < f_{b,\max} \text{ and } s_b = 0 \\ f_{b,\max} & \text{if } T_i > f_{b,\max} \text{ and } s_b \leq s_{b,\max} \\ T_i \cong H_i & \text{if } s_b > s_{b,\max} \end{cases} \quad (29)$$

19 where $f_b, f_{b,\max}, s_b, s_{b,\max}$ are the generic force, the maximum allowable brake
 20 force, the generic displacement and the maximum brake displacement,
 21 respectively. In order to take into account such a mechanical behaviour, the
 22 above formulated model can be modified as follows: i) check if the force in a
 23 generic cable reaches the maximum allowable brake force, $f_{b,\max}$; ii) if the
 24 previous condition is fulfilled (ie. $T_i > f_{b,\max}$) increase the cable length by a small
 25 fraction Δs_b of the original cable length in order to obtain the new effective cable
 26 length, $L_i = (l_i + \Delta s_b) \cdot (1 + H_i / E_i A_i)$; iii) determine again the force in the cable
 27 with such a new length by using Eqs (11, 12); iv) check whether the new force is
 28 lower than $f_{b,\max}$ otherwise go to step ii) and increase again the cable length.

1 Repeat the above procedure until the fulfilment of the condition $T_i < f_{b,\max}$ or
2 continue without any other modification if the maximum brake elongation $s_{b,\max}$
3 has been reached.
4 Finally, the energy dissipated by the brake during its service can be easily
5 obtained as:

$$E_b = f_{b,\max} \cdot s_b \quad (30)$$

6

7 **4. Numerical applications, experimental validation** 8 **and discussion**

9 **4.1. Parametric numerical examples**

10 In the present section a representative example of retention barrier is considered
11 and solved through the developed model, in order to simulate its mechanical
12 behavior by varying some parameters of the barrier itself and of the debris flow.
13 In particular, the effect of the stiffness of the net connecting to the horizontal
14 cables and, for a given barrier configuration, the influence of the debris flow
15 velocity v_0 are considered.

16 The parameters of the flowing debris and those of the barrier are the following:

17 $k = 0.8, \alpha = 2.0, h_0 = 0.7m, \theta = 40^\circ, h_B = 5.0m, p = 1.0m,$

18 $f_{b,\max} = 60kN, s_{b,\max} = 0.5m$ while the transversal cables representing the net have

19 been assumed to be characterized by the ‘equivalent’ cross sectional area equal to
20 the following values: $A_t = 0.5mm^2, 10mm^2, 50mm^2, 200mm^2$. In order to

21 investigate the effect of the debris flow velocity (by assuming for such a case

22 $A_t = 0.5mm^2$), the following values have been considered:

23 $v_0 = 2.0m/s, 4.0m/s, 8.0m/s$. The geometry of the barrier is reported in Fig. 11a

24 (the cable No 1 located at $z = 0$ is assumed to be fixed, i.e. it does not undergo

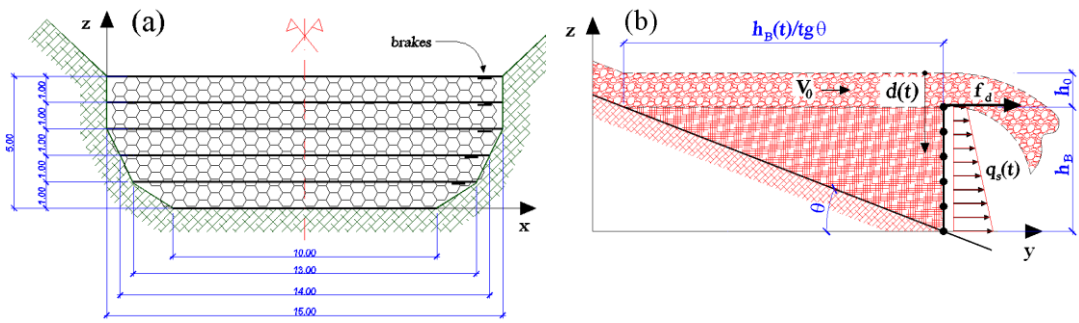
25 any significant displacement), while in Fig. 11b the scheme of the so-called drag

26 force f_d – occurring when the allowable volume for the debris accumulation is

27 completely filled by the flowing material – is represented when the flow continues

28 to take place above the barrier.

1



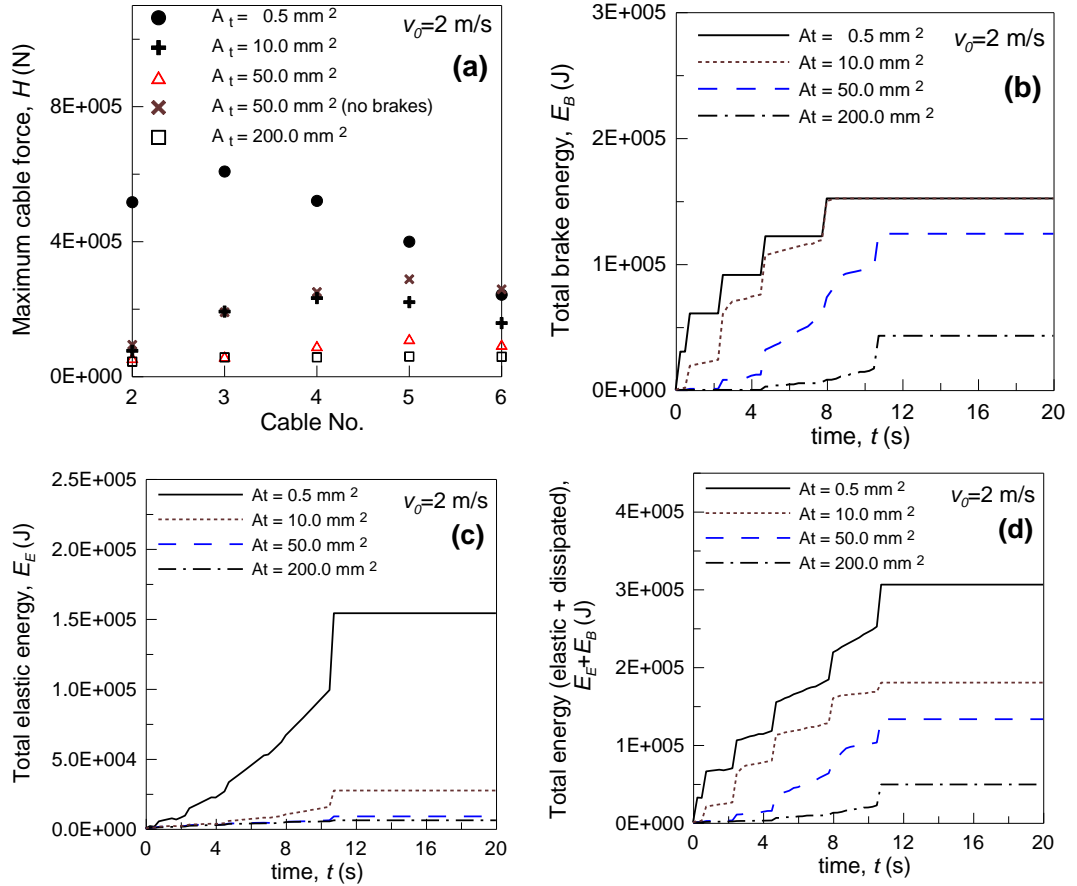
2 *Fig. 11. Geometrical dimensions of the considered barrier (a) and scheme of the*
3 *drag force occurring when the debris flow continues above the barrier (b)*
4 *(dimensions are expressed in m).*

5

6 In Fig. 12 the effect of the different values of the cross section of the vertical
7 cables is presented. In particular in Fig. 11a the maximum tensile force in the
8 cable during the whole impact period of the debris against the barrier is presented;
9 as can be noted the maximum tensile force reduces by increasing the stiffness of
10 the net and such a maximum force becomes almost identical for all the cables. On
11 the other hand, for a weak net the cables are subjected to very different maximum
12 force values which are also higher than those calculated with strongest nets. The
13 case of a barrier without brakes (with $A_t = 50\text{mm}^2$) is also reported; the forces in
14 the cables are obviously much higher than those obtained for the same barrier with
15 the brakes.

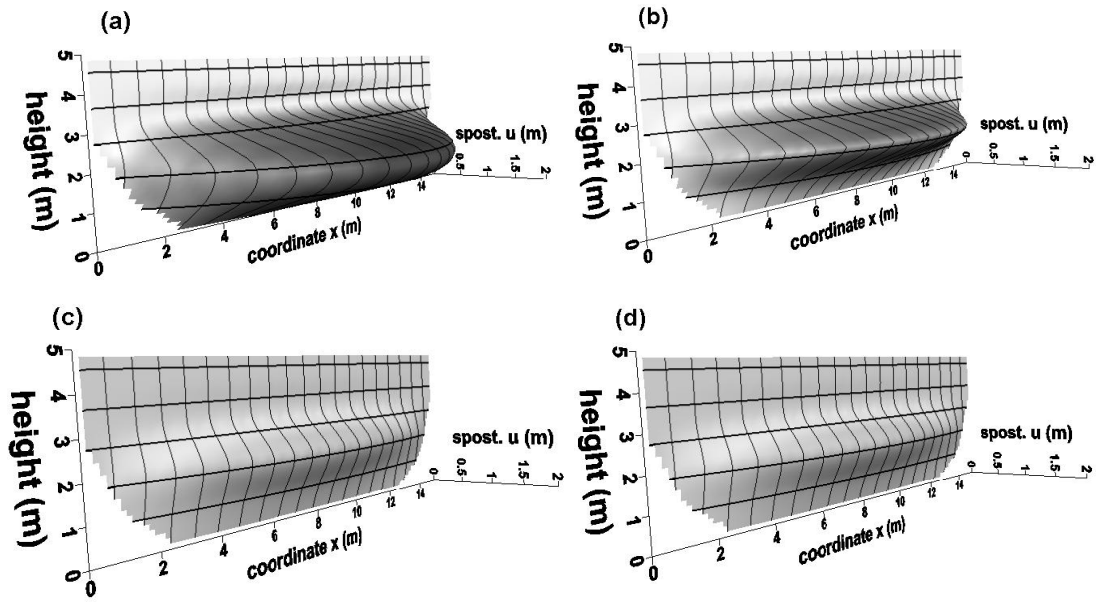
16 In Fig. 12b the energy dissipated by all the brakes during the impact is
17 represented. As it can be noticed, the total final amount of dissipated energy
18 decreases when the net stiffness increases since the forces occurring in the cables
19 are lower when the net is stiffer and therefore the brakes do not reach their final
20 allowable stroke. In Fig. 12c, d the total elastic energy stored in the barrier and
21 the sum of the total elastic and dissipated energy are represented vs time,
22 respectively. The trend shown by the curves for different net stiffness is in
23 accordance with the forces developing in the cables during the phenomenon. It
24 can be also observed that, after reaching the complete filling of the barrier (see
25 Fig. 11b), the phenomenon reaches a steady state and the above quantities remain
26 constant with time.

1 In Fig. 13 the deformed pattern of the barrier at the time $t=1$ s is represented for
 2 the four different transversal nets; it is apparent, once again, the load distribution
 3 effect of the transversal net on the horizontal cables of the barrier.
 4



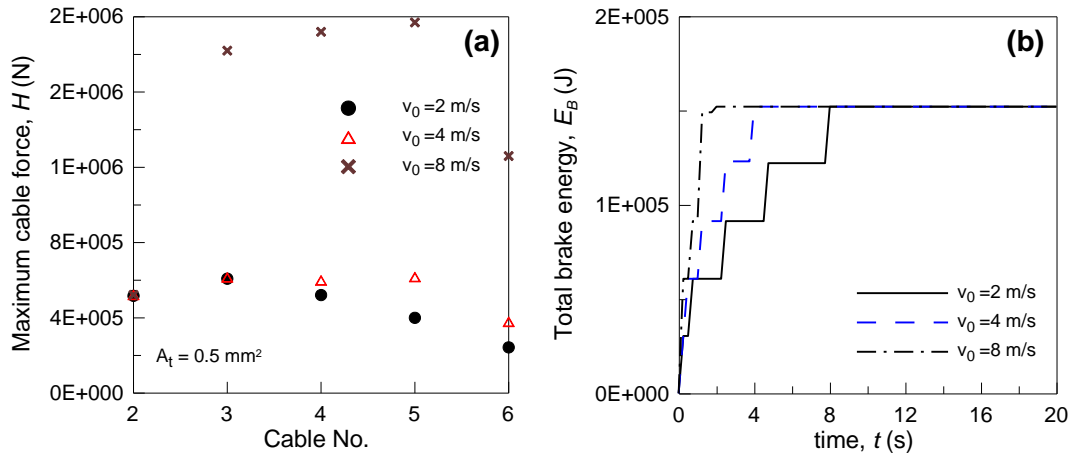
5 *Fig. 12. Barrier with different stiffness of the superposed steel net: maximum*
 6 *tensile force in the cables (a), dissipated brake energy of the barrier (b), elastic*
 7 *energy of the barrier (c) and total (elastic + dissipated) energy of the barrier (d)*
 8 *vs the time t .*

9
 10
 11
 12
 13
 14
 15
 16



1 Fig. 13. Deformed pattern of the barrier with different stiffness of the superposed
 2 steel net at the time $t=1s$: case of $A_t = 0.5mm^2$ (a), $A_t = 10mm^2$ (b), $A_t = 50mm^2$
 3 (c) and $A_t = 200mm^2$ (d).

4
 5 Finally the effect of the debris flow surges velocity is herein considered. In Fig.
 6 14 the maximum tensile force attained in the different cables of the barrier is
 7 represented for the three assumed debris flow surges velocity
 8 ($v_0 = 2.0m/s, 4.0m/s, 8.0m/s$). It appears as the force in the bottom cable (No.
 9 2) is not influenced by v_0 since the static load produced by the accumulated
 10 material prevails over the dynamic force; on the other hand, the velocity influence
 11 becomes relevant for the cables placed at higher levels. In Fig. 14b the total
 12 amount of dissipated energy is represented; it appears that such total energy at the
 13 end of the phenomenon is the same for the different velocities since all the brakes
 14 reach their maximum allowable sliding length. In the case of higher velocities of
 15 the flow surges, the maximum brakes displacement is reached in a shorter time
 16 with respect to lower velocities.
 17



1 *Fig. 14. Effect of the debris flow velocity. Maximum tensile forces in the cable*
 2 *during the debris impact (a) and total energy dissipated by the brakes vs the time t*
 3 *(b) for different values of v_0 .*

6 **4.2. Simulation of a full scale test of a retention barrier**

7 In order to assess the reliability of the proposed analytical model, the simulation
 8 of a full scale test on a barrier is considered hereafter.

9 The test was carried out inside a limestone quarry located in the Pieve d'Alpago
 10 district (Belluno province, Northeastern Italian Alps); the artificial channel was
 11 built by re-shaping an existing natural impluvium and the barrier was located at its
 12 bottom (Fig. 4). The obtained artificial channel was 2 m large and 48 m long, with
 13 an average slope of 40° . The material used to simulate the flow was constituted by
 14 well-graded limestone blocks with diameter ranging from few cm to 1.5 m. Due to
 15 the particular geometry of the channel, to the nature of the material and to the
 16 machinery used to mobilize it, it was not possible to keep the material saturated;
 17 however, the effects on the barrier in terms of deformation and forces were in
 18 good agreement with other small scale and large scale test results available in
 19 bibliography (Davies [52], Iverson [53], Canelli [41]).

20 During the test, both deformation and horizontal cable forces were measured
 21 using photogrammetric techniques and load cells, respectively. The
 22 photogrammetric restitution was based on the pictures taken by a couple of frontal
 23 high definition camera that shot at a speed of 23 frame per second. The load cells,
 24 with a maximum measurement range of 1000 kN, were mounted on each of the

1 five horizontal cables as depicted in Figure 2 and their data were recorded at 1 Hz
2 frequency.

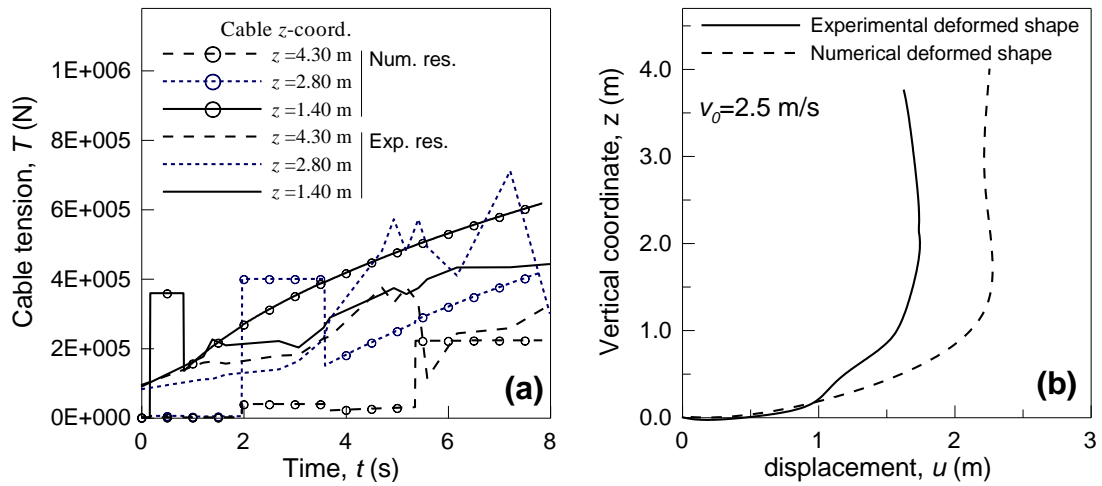
3 The registered flow velocity was 2.51 m/s on average with measured peaks of 9
4 m/s, the total volume stopped at the barrier was of approximately 400 m³, the
5 average flow height h_0 was equal to 0.7 m while the material density was
6 estimated in 1790 kg/m³. The test came to the end with the filling up of the whole
7 barrier, no overflow was allowed in order to preserve the safety at test site.

8 The structure under consideration is characterized by an average span of about
9 17.00 m while its height is equal to 4.00 m; it is composed by four main
10 horizontal double steel cables (6x19 class according to UNI EN 12385-4) having
11 diameter $\phi 20$ mm, fixed at the extremities to foundations grouted inside the
12 channel shoulders. The four horizontal main cables are mounted at a relative
13 vertical distance p equal to about 1.33 m (Fig. 2). A steel ASM 3-4- 350/200 ring
14 net made by $\phi 350$ mm rings, connected at four point contact is linked at the
15 horizontal cables (Fig. 3). The rings are formed by a single steel wire (1380
16 N/mm² minimum tensile strength) having a diameter $\phi 3$ mm and rolled up in 10
17 loops and 2 spirals. The lower cable was fixed at the bottom surface of the
18 channel in the real test, by means of several anchors; in order to account for the
19 effect of those restrains in the analytical model, since the proposed simplified
20 analytical model does not allow the application of restraint along the main cables,
21 a cable with a larger cross sectional area (20 times the area of the others) was
22 adopted. This assumption implies that the horizontal displacements of the lower
23 cable are negligible and its calculated axial forces are omitted for the comparison
24 between real case and numerical results.

25 The analytical model has been solved by assuming $\alpha = 1.5$, $k = 0.5$ to describe
26 the loads on the barrier; the value of the empirical coefficient α and of the earth
27 pressure coefficient k were recovered through back analysis, considering the
28 indications of Canelli et al. [41] and Bugnion et al. [54] while the exponent m of
29 the functions $r(z_j, z_i)$ relating each cable with the others - i.e. for the assessment
30 of the cables interaction - have been calculated according to the above described
31 GA procedure.

32 The values of the coefficients necessary for the evaluation of the forces induced
33 by the debris flow against the barrier (Eqs 1, 3), have been performed by
34 following the considerations below.

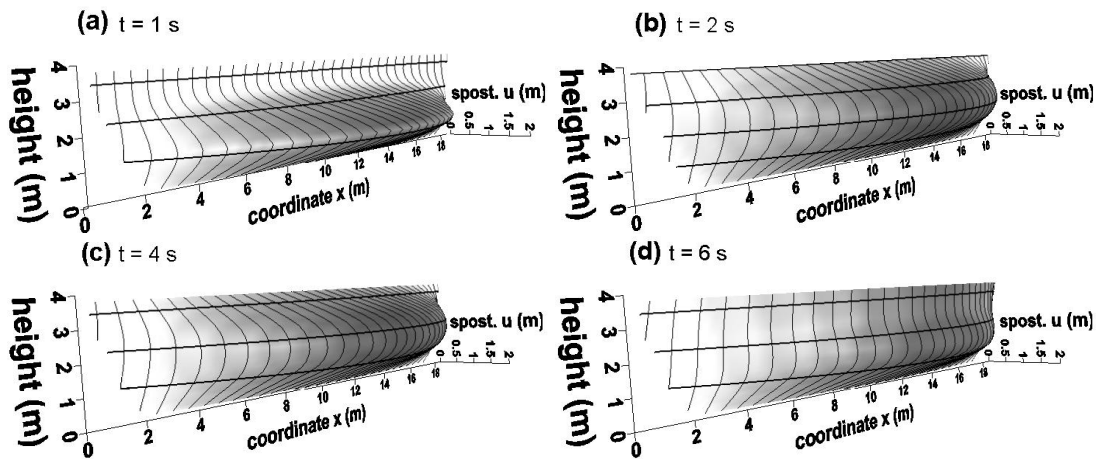
1 Bugnion et al. [54] have performed several tests of flow against obstacles and
 2 computes the α value. They shows that 2 is the maximum value. For this reason
 3 the Authors considered this value in the initial phase of development of the work.
 4 For the coefficient of earth pressure k , the value $k = 0.5$ was chosen because Kwan
 5 and Cheung [40] suggested a maximum value of 1 in undrained condition but we
 6 could observe a condition of partial saturation during the flow and of good
 7 drainage during the impact of the debris against the barrier. Therefore, the friction
 8 angle of the debris accumulation behind the barrier was originally assumed
 9 between 20° and 30° , converging to the value of 20° through a back analysis
 10 procedure developed in order to better fit the experimental results.
 11



12 *Fig. 15. Comparison between experimental and analytical results of: (a) tension*
 13 *forces in the horizontal structural cables vs. time; (b) maximum deformed shape*
 14 *of the barrier at the midspan vertical section.*

15
 16 In Fig.15 (a) the forces measured in each cable (identified through its co-ordinate
 17 position z) during the test are plotted against time, together with those determined
 18 using the proposed analytical model. In Fig. 15 (b) are reported both the shape of
 19 the deformed barrier measured at the central vertical section at the end of the test
 20 and that calculated using the proposed model. Although some differences
 21 between experimental and numerical results were obtained, especially for what it
 22 concerns the barrier deformation, the induced state of traction in the cables are in
 23 good agreement. This is possibly due to the initial state of stress in the cables,
 24 which is originally applied during the structure assembly; this pretension is not
 25 influencing the final state of stress induced by the debris flow impact while it

1 does, instead, influence its deformation particularly at the beginning and at the
 2 end of the loading process. Furthermore, the lower portion of the barrier (lower
 3 horizontal cable) is free to deform along its length in the proposed model (its
 4 displacement is fictitiously limited by adopting a cable cross section area greater
 5 than its effective value, as already discussed) while, in the real case, is fixed at the
 6 channel surface by means of eyebolts. These boundary conditions can be
 7 reconsidered and improved in future development of the work.
 8 Regarding the duration of the test reported in abscissa in Fig. 15 (a), it should be
 9 considered that, while in the analytical model it is calculated using the geometry
 10 of the channel and the velocity of the debris surge, for what it concerns the real
 11 test it is determined considering the debris flow as if it was flowing at a constant
 12 rate, neglecting the interruptions that occurred between surges due to the above
 13 described operational limitations.
 14



15 *Fig. 16. Deformed patters provided by the present model for $t=1.0$ s (a), $t=2.0$ s*
 16 *(b), $t=4.0$ s (c) and $t=6.0$ s (d) (see Fig. 15b) corresponding to the simulation of*
 17 *the on site tests described above.*

18
 19 In Fig. 16 a full 3-dimensional reconstruction of the net deformed pattern during
 20 the loading process is also given; as can be observed it shows how the method can
 21 realistically reproduce the barrier deformation with the time, providing the net
 22 shape as the flow phenomena proceeds and the debris accumulates behind the
 23 retention barrier. This results can be usefully applied in the future for setting up a
 24 real time net monitoring system able to define threshold values to be controlled in
 25 situ by means of specific measuring devices.

1 The energy dissipated by the barrier upon the impact with the debris flow can be
 2 calculated by adding two terms: the first derived from the dissipation of the brake
 3 devices E_b and the second induced by the elastic deformation of the supporting
 4 cables E_E (see Eq. (31)).

$$\begin{aligned} E_b &= f_{b,\max} \cdot s_b, \\ E_E &= 1/2(LH^2 / EA) \end{aligned} \quad (31)$$

5 In our simulation of the test, the amount of energy dissipated at the end of the
 6 impact phase is approximately equal to 286 kJ.
 7 Sun & Law [55] proposed several analytical solution for the determination of the
 8 design impact energy of the barrier based upon pile-up or run-up mechanisms. In
 9 our case, the most appropriate formulation appears to be the run-up mechanism
 10 with the height of the final debris accumulation equal to the height of the barrier.
 11 The related equation, proposed by Sun & Law [55] and rewritten with our
 12 notations becomes:

$$E_B = \frac{\rho_d Fr v_0 h_b^2}{4h_0 \tan(\theta + \alpha)} - \frac{\rho_d g Fr h_b^3}{3h_0 v_0 \tan(\theta + \alpha) \sin(\theta + \alpha)} (\sin \alpha + \mu \cos \alpha) \quad (32)$$

13 The application of Eq. (32) to the Pieve d'Alpago test, considering the parameters
 14 acquired from the back analysis described above, gives a design impact energy of
 15 the barrier E_B equal to 452 KJ. This result is obtained considering the angle
 16 between the horizontal and the upper surface of the debris accumulated behind the
 17 barrier substantially horizontal ($\alpha = 1^\circ$) as observed during the test. The interface
 18 friction coefficient μ is determined, using Eq. (33) described in [55] through a
 19 back analysis procedure aimed at obtaining the impact duration T_f comparable
 20 with that calculated by the proposed analytical model (approximately 8 s).
 21

$$T_f = \frac{h_b^2}{2v_0 h_0 \tan(\theta + \alpha)} \quad (33)$$

22 The above consideration indicates that around 37% of the design impact energy
 23 of the debris flow is dissipated internally during the impact phase and only the
 24 remaining portion is transferred to the barrier.

1 **5. Conclusions**

2 The energy associated with debris flows along with their velocity, active volumes
3 and run out distances have often made these phenomena very destructive and
4 dangerous. The design of retention devices, which are often a must in populated
5 area or wherever it is necessary to limit the destructive effects of debris flows, is
6 often carried out using previous experiences and subjective knowledge of the
7 phenomena mechanics. Analytical approaches are seldom used and generally
8 based on numerical modelling (FEM). However, the numerical modelling of
9 these structures, which should be carried out considering the debris flow impact
10 dynamics, can turn out to be very complicated and not always reliable in
11 applicative cases. For these reasons, the need of a sound design instrument, easily
12 applicable in standard, is becoming of paramount importance and is not yet
13 available to practitioners.

14 In the present paper a simplified analysis of the mechanics of debris-flow is
15 considered in order to estimate the forces developed by such a flow impacting on
16 a retention barrier. Then, an analytical simplified structural model of cable-like
17 retention barriers is developed, based on the equation of equilibrium of wires
18 under large displacements condition, and the restraining forces as well as the
19 cable stresses are finally estimated. A parametric study has been presented, in
20 order to demonstrate the capability of the proposed model to capture all the main
21 mechanical aspect occurring during the impact of a debris flow against a flexible
22 structure. The boundary conditions for the lower cable are the same as those listed
23 for the other cables (i.e. anchored at the channel sides), avoiding to consider the
24 lower cable connected to the channel bottom. This geometrical configuration is
25 often used, in consideration of the scarce mechanical reliability of the debris
26 deposited along the channel.

27 The comparison between experimental and numerical results has been presented,
28 as well. The satisfactory agreement hereby shown, enable us to state that the
29 present approach is promising, even though, some differences have been recorded;
30 such discrepancies are possibly due to the simplifying variables introduced in the
31 calculation and to some of the theoretical assumption needed to achieve an
32 analytical solution of the problem. However, this work represents a starting point
33 that will need further development along with additional validations. At present,
34 new experimental data are processed (either taken from literature or from direct

1 measurements) and several parametric analysis are under development in order to
2 define the sensitivity of the model upon changes in the structural geometry or in
3 the debris flow features.

4

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10

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