Vagnon, F; Ferrero, A.M.; Umili, G.; Segalini, A.. A Factor Strength Approach for the Design of Rock Fall and Debris Flow Barriers. GEOTECHNICAL AND GEOLOGICAL ENGINEERING. None pp: 1-13.
DOI: 10.1007/s10706-017-0269-x

Geotechnical and Geological Engineering

A factor strength approach for the design of rock fall and debris flow barriers

--Manuscript Draft--

Manuscript Number:	GEGE-D-16-00128R1
Full Title:	A factor strength approach for the design of rock fall and debris flow barriers
Article Type:	Original Research
Keywords:	Rockfall; Debris Flows; Eurocode 7; Limit States Design
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Funding Information:	
Abstract:	This paper discusses the applicability and the limitations of an approach to the limit states design of flexible barrier in which the soil/rock strength are factored as required in the European construction code. It shows as this approach has different implications if it is applied to the same kind of structure when loaded by different phenomena (rockfall and debris flow in particular). Flexible barriers are common countermeasures to protect from rockfall hazard and to restrain debris flow events. Even if an intense scientific production has demonstrated the difference between the two phenomena, the protection systems are still often designed in the same way. Additionally, the Eurocode 7 (EC7), which is the European Standard concerning geotechnical design, has not been conformed to these kinds of structures and consequently a relationship between the reliability of the system and the partial factors does not exist. Since most of the parameters that rule these systems are not even considered in the code, the Authors propose the study of two cases, in which rockfall and debris flow occur, respectively, to analyse the applicability and the limitations of EC7 principles to design the suitable kind of structure.
Response to Reviewers:	COMMENTS TO THE AUTHOR: Reviewer #1: In this manuscript, the authors propose an analysis in the framework of EC7 for rockfall and debris flow phenomena, trying to evaluate the possibility to apply a partial factors approach for these particular slope movements. The work is based on the application of EC7 to two case histories one of rock fall and one of debris flow respectively. The case histories are well documented and properly developed according to all phases from rock mass characterization to the block path or flow runout evaluation. Eventually, the authors conclude that the set of partial factors presented in EC7 is

incomplete for these kinds of applications, since many important parameters related to rock and soil mechanics are not considered and that a complete reliability analysis that takes uncertainties into account is extremely convenient to quantify the failure probability of these kinds of structures.

The obtained results are sound and convincing and consistent with the applied methodology. The paper is interesting for the scientific community since no guidelines are available for the design of flexible barriers.

To the best, knowledge of this reviewer, the topic of this paper is overall within the major scopes of the journal and may be of some interests to its general readers and, in particular, those specialized in civil and environmental engineering. The manuscript can be considered for publication with minor revisions. It is recommended that the Authors consider the following points for clarification and completeness before publication:

Page 2
Line 21 - The percentage of 0.0072% refers to a uniform probability of failure for a 50 year reference period and for a RC2 reliability class, as listed in Table B2 EN 1990:2002. It would be better to change that value introducing the cited table.
We added the following statement and the required table:
“The structures are classified into three main reliability classes (Table 1), assuming different reliability targets and consequently different probability of failure”

Line 29 - Introduce abbreviation "DA" after design approach
Done.

Page 3
Line 13 - It is not clear for this reviewer the meaning of "stress analysis is suggested". Please, give more details about it. Revise that paragraph.
We modified the paragraph and added the following sentences to better explain the concept:
“In particular, the force approach allows us to consider both the dynamic and static effects of the impacting front on the barrier. Moreover, all the involved parameters in the impact phase (particularly velocity and flow thickness) show marked time dependence: consequently energetic approaches cannot take into account this evidence that is better simulated using force approaches.”

Lines 25 to28: this reviewer think that this paragraph is unnecessary.
The paragraph has been deleted.

Line 35: Explain the meaning of "reliability target".
We added the following sentences:
“The reliability target is assigned in function of the importance of the designed structure and the reference period of 1 year or 50 years. In brief, the reliability target corresponds to levels of safety of the structures and it is related to the associated probability of failure. In particular the probability of failure is expressed through a performance function that for each geotechnical design situation is:”

Line 60: delete Design Approach. Use abbreviation.
Done.

Page 5
Line 13: better explain the meaning of aleatory and epistemic uncertainties
We added the following sentences:
“In particular, sources of errors in sampling are classified as:
- Sampling error;
- Estimation error;
- Measurement error.
These errors are essentially linked to the lack of knowledge (Baecher and Christian 2003), therefore innovative techniques, which allow one, for example, to investigate large portions of rock mass or portions of it otherwise difficult to approach, provoke a consequent decrease of the epistemic uncertainty (Guo and Du 2007; Bedi and Harrison 2013).”

	Page 6 Line 9-12 Better explain the use and reason of interval analysis We added the following paragraph: “Concerning debris flow phenomena, the availability of data is inadequate: data from real events are not many; on the other hand, data from experimental test are copious but affected by scale factors. As a consequence, the available databases come from back analysis of single events, randomly collected and, often, comparing phenomena from different geological domain. Thus, the nature of these parameters is epistemic and, consequently, the use of statistical methods to analyse these phenomena is affected by limitations. In brief, for any given amount of knowledge – and hence degree of uncertainty – there is an optimal statistical model that should be applied (Harrison, 2014). Thus, an interval analysis was performed and for each parameter, a lower and an upper limit value were chosen. All the arithmetical operations required to analyse intervals were performed by considering all the possible combinations of the involved parameters.” Even if the paper is well written, the manuscript will largely benefit from polishing the English. Done.

A factor strength approach for the design of rock fall and debris flow barriers

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Abstract

This paper discusses the applicability and the limitations of an approach to the limit states design of flexible barrier in which the soil/rock strength are factored as required in the European construction code. It shows as this approach has different implications if it is applied to the same kind of structure when loaded by different phenomena (rockfall and debris flow in particular).

Flexible barriers are common countermeasures to protect from rockfall hazard and to restrain debris flow events. Even if an intense scientific production has demonstrated the difference between the two phenomena, the protection systems are still often designed in the same way. Additionally, the Eurocode 7 (EC7), which is the European Standard concerning geotechnical design, has not been conformed to these kinds of structures and consequently a relationship between the reliability of the system and the partial factors does not exist.

Since most of the parameters that rule these systems are not even considered in the code, the Authors propose the study of two cases, in which rockfall and debris flow occur, respectively, to analyse the applicability and the limitations of EC7 principles to design the suitable kind of structure.

Keywords

Rockfall; debris flows; Eurocode 7; limit states design

1. Introduction

Specific guidelines dealing with the design method to be used for rockfall barriers do not exist. The procedure to evaluate the energy that the barrier is able to dissipate remains a choice to be made by the designers. In fact, European Technical Approval Guidelines (ETAG 027) accurately define only the standard procedure to verify the material qualifications and the performances of the falling rock protection kit. ETAG 027 makes only a suggestion concerning two different energy levels that the barrier should resist in order to be certified:

- MEL (Maximum Energy Level): the maximum kinetic energy retained by a homogeneous block with regular geometry that impacts at a speed above 25 m/s and is stopped by the barrier;
- SEL (Service Energy Level): the kinetic energy (at least 1/3*MEL) that the barrier is able to dissipate while stopping a block for two consequent impacts without undergoing to any maintenance or part substitution.

With regard to debris flow, flexible barrier design is still an open issue. Actually there are no official European guidelines and there are very few universally recognized methods to design this type of protection structures. New regulations concerning the definition of the flexible kits for retaining debris flows (EAD 340020-00-0106) are forthcoming, but as well as ETAG 027, they concern only the experimental tests to certify the resistance of the barriers.

The international standards treat these phenomena just marginally. The European Standard concerning geotechnical design (EC7), is a clear example of this fact: although protection structures are widely used, there are no specific references in it. The code is based on the Limit State Design (LSD) principle, whose philosophy is to provide structures with a uniform probability of failure. The structures are classified into three main reliability classes (Table 1), assuming different reliability targets and consequently different probability of failure. The magnitude of the partial factors, reported in the code, has been derived from the calibration performed during a long experience of building, but several authors outlined a discrepancy between the failure probability computed taking into account the uncertainty distribution and the one obtained with the partial factors application (Callisto, 2010).

Furthermore, EC7 principles do not cover the entire range of geotechnical problems and refer mainly to soil and to the interaction between soil and a rigid structure: rockfall and debris flow phenomena, as well as flexible countermeasures to prevent them, are not treated. There is a lack of partial factors for rock engineering, and this renders the various analytical Design Approaches (DA) inapplicable to anything except spread foundations (Harrison et al. 2014). Moreover, rock engineering design is included in the scope of EC7, but this is often overlooked (Lamas et al. 2014).

A discussion about the possibility to apply LSD to rockfall and debris flow phenomena is necessary, since the real applicability of the partial factors approach has never been investigated.

In this paper the Authors want to focus on the potentiality and limitations of the application of LSD to rockfall and debris flow flexible barriers and to give suggestion on possible research development in the field. In summary, the Authors try to answer the following questions: is it possible to design flexible barriers following the EC7 criteria? Which parameters and, consequently, partial factors have to be considered for short and long term design situations? Which are the uncertainties that affect this process and the associated probability of failure?

An analysis in the framework of EC7 has been conducted on two sites subjected to rockfall and debris flow, respectively, and on a hypothetical flexible barrier exposed to these phenomena. A critique review of the geotechnical parameters useful for the design has been performed considering interval analysis and evaluating uncertainties in each step of the process.

2. Flexible barriers working principles

Deformable restraining net barriers have been largely used in mountainous areas to protect urbanized zones and infrastructures against collapses of rock blocks. These countermeasures are made of a light structure in which a certain number of posts keep in position a steel mesh and a series of steel cables: this mesh stops the moving block and transfers all the forces to the anchors in the ground (Peila et al, 1998). Dissipating systems are usually installed on each cable in order to reduce the kinetic energy of the block, taking advantage of friction effects and large cable deformation.

These countermeasures are designed on the basis of volume, trajectory and kinetic energy of falling blocks. In particular, the definition of the design block is a key point of the design in order to define barrier resistance; in fact, it is strongly affected by uncertainties related to the evaluation of spacing and orientation of rock discontinuities (Ferrero et al. 2016a). Nowadays, the use of remote sensing techniques offers a great opportunity for acquiring spatial information of rock masses: laser scanner and photogrammetric surveys allows one to obtain high resolution Digital Surface Models (DSM). These models can be used as representation of rock masses and investigated with dedicated codes (Ferrero 2009; Sturzenegger and Stead 2009; Lato et al. 2012; Vöge et al. 2013; Riquelme et al. 2014) in order to build large databases of rock discontinuities, useful to perform statistical analyses regarding kinetic energy and volume of rock blocks.

Rockfall barrier design is based on the hypothesis that the energy retained by the block is instantaneously and completely transferred to the barrier upon impact (Peila and Ronco 2009; Giani et al. 2004), consequently this kind of structures is commonly designed with an "energy approach", comparing the kinetic energy of the falling blocks with the resistance energy of the barrier determined according to ETAG027.

Since barriers used for debris flow protection are quite similar to those adopted for rockfall phenomena, they are currently designed in the same way, even if the two phenomena are completely different (Roth et al. 2004; Segalini et al. 2008; Ferrero et al. 2010). In fact, with regard to the impact, flow energy is not instantaneously transferred to the barrier: in fact, there is a continuous dissipation during barrier filling due to the friction forces within the material (during deposition phase) and the drainage capability of the barrier (Wendeler and Volkwein 2015). On the basis of these evidences, the energetic approach used for rockfall barrier design is not suitable and applicable to debris flow barriers and a stress analysis is suggested. In particular, the force approach allows us to consider both the dynamic and static effects of the impacting front on the barrier. Moreover, all the involved parameters in the impact phase (particularly velocity and flow thickness) show marked time dependence: consequently energetic approaches cannot take into account this evidence that is better simulated using force approaches.

Some analytical and numerical models to compute the induced state of stress in the barrier have been recently proposed (Brighenti et al. 2013; Volkwein et al. 2011) but they require to know the characteristics of the debris flow during the impact, in term of velocity and thickness. Furthermore, none of them are universally recognized and a complete design procedure is still under development.

3. LSD and EC7: principles and philosophy

LSD deals with a prediction of how the system will perform when it is near failure (Baecher and Chritstian, 2003). Failure, in this meaning, can be used either as ultimate failure (collapse) or as conditions affecting serviceability (excessive deformation). Thus LSD is defined as that condition under which a structure or its components no longer perform an intended function (Allen, 1994; Simpson et al., 1981).

EC7 is one of the European standards concerning all aspects of geotechnical design, providing common rules to check construction strength, stability and durability against extreme loads. It deals with constructions in or on the ground, which is defined as "soil, rock, fill in place prior to the execution of the construction works".

EC7 is based on the LSD, which is a semi-probabilistic method in which partial factors are applied to characteristic parameter values in order to take into account the uncertainties and to achieve a design associated to a certain reliability target (Fig. 1). The reliability target is assigned in function of the importance of the designed structure and the reference period of 1 year or 50 years. In brief, the reliability target corresponds to levels of safety of the structures and it is related to the associated probability of failure. In particular the probability of failure is expressed through a performance function that for each geotechnical design situation is:

$$E_d \leq R_d \tag{1}$$

where E_d is the design effect of actions and R_d is the corresponding design resistance.

In particular, Equation 1 refers to geotechnical limit states (GEO) and structural limit states (STR).

The design effect of actions is evaluated considering partial factors that could be applied either to the actions themselves (F_{rep}) or to their effects (E):

$$E_d = E\left\{\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d\right\} \tag{2a}$$

or $$E_d = \gamma_E E\left\{F_{rep}; \frac{X_k}{\gamma_M}; a_d\right\} \tag{2b}$$

where F_{rep} is the representative value of action, X_k the characteristic value of a material property, a_d the design value of geometrical data, γ the partial factor for the effect of action (γ_E), for the action (γ_F) and for the soil parameter (γ_M), respectively.

The same considerations can be made for the design resistances: in fact, partial factors may be applied either to ground properties (X), resistance (R) or both, as follows:

$$R_d = R\left\{\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d\right\} \tag{3a}$$

$$R_d = R\left\{\gamma_F F_{rep}; X_k; a_d\right\}/\gamma_R \tag{3b}$$

$$R_d = R\left\{\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d\right\}/\gamma_R \tag{3c}$$

where γ_R is the partial factor for a resistance.

LSD formalization in technical codes has followed two main paths: an approach that factors loads and overall resistance and an approach that factors loads and strength parameters (Becker, 1996). This has produced three different DA to verify Equation 1:

- DA1, in which partial factors are applied to actions (Combination 1) and to material parameters (Combination 2).
- DA2 where factors are applied to actions and to resistances simultaneously.
- DA3 in which partial factors are applied only to structural actions (not to geotechnical actions) and to material properties.

Partial factors for each combination are listed in Table 2.

3.1 Rockfall and debris flow phenomena in EC7

Since rockfall and debris flow phenomena (and their interaction with flexible barriers) are important geotechnical problems, widely discussed in literature and of great interest for hazard assessment and protection, it is opinion of the Authors that retaining structures, such as net barriers, should be treated in EC7 and accurate studies should be carried out in order to assess standard design procedures.

Moreover, debris flows are borderline phenomena between rock mechanics and soil mechanics due to their nature, therefore a particular section of the regulations should be dedicated to them.

However, despite this lack of regulations an analysis in the framework of EC7 was performed to understand and, possibly, to suggest methods to overcome the current limitations.

Reading the EC7, there are no direct references to flexible retention structures against rockfall and debris flow hazard: only in Section 11.5.2, concerning overall stability, it is possible to find a statement in which net barriers are cited: "*[…]in cases where reliable provisions to prevent rock falls are not feasible, rock falls should be allowed to occur with the provision of nets, barriers or other suitable provision to trap the falling rock*". However, in the section dedicated to retaining structure they are not contemplated: only gravity walls, embedded walls and composite retaining structures (mix of the previous two types) are considered.

The first question is in which category flexible barriers should be included: by analysing Section 2.1 (EN-1997-1 §11-21), they could be considered both in Geotechnical Category 2 or 3. In fact, protection fences can be compared with structures retaining soil/rock (Geotechnical Category 2) and, at the same time, structures involving abnormal risks, or unusual or exceptionally load conditions (Geotechnical Category 3). The choice of one category respect to the other implies different design aspects, therefore is not only a matter of classification.

The second aspect to take into account is the possibility to consider short and long-term conditions: Fig. 2 is useful to introduce and explain this concept.

Short-term condition represents the period immediately after barrier construction (Fig.2a and 2c), in which the structure is exposed only to atmospheric agents until a rockfall or debris flow event occurs. In this situation the condition imposed by Equation 1 shall be verified. Is it possible to forecast long-term conditions, especially if the barrier is subjected to several impacts during its life (Fig.2b and 2d)? And if yes, how is it possible to guarantee the same safety degree? The EC7 demands to verify these aspects but, currently, there are no helpful methods to answer these questions.

Furthermore, there are many questions related to the choice of the main parameters that are not treated. For instance, the definition of the design block in rockfall events is strictly influenced by discontinuities orientation and spacing in the originating rock mass. These measurements can be obtained following the traditional methodology, using compass and clinometers, or by using remote sensing tools (Slob et al. 2005; Ferrero et al. 2009; Sturzenegger and Stead 2009; Lato and Vöge 2012; Riquelme et al. 2014). Discontinuity data obtained from remote sensing tools need to be reliable and representative of the considered rock mass, therefore great attention must be paid to their accuracy and completeness. These measurements are affected by both epistemic and aleatory uncertainties: epistemic ones are directly correlated to the characteristics of the survey method, while aleatory ones are due to the natural variability of discontinuities characteristics inside the rock mass. Remote sensing tools play a fundamental role in the data acquisition step (Ferrero et al., 2014), but a robust statistical data treatment is required in order to obtain useful input data for stability analyses and structural design.

The same considerations can be made for debris flow events: the determination of velocity and depositional height are closely related to the employed method (numerical or empirical), to the considered unstable volume and to the rheological law used to simulate the flow. Since a wide database of historical events and reliable site-specific statistics are not available, it is very difficult to find a probability distribution of the involved actions. For debris flows the Authors suggest the use of interval analyses (Moore 1966). If the degree of knowledge related to a parameter, in this case velocity and thickness, is very low (epistemic uncertainty is predominant), it is possible to use an interval that bounds a value between an upper and lower limit. This allows for the evaluation of a range of possible actions acting against the barrier. Moreover, the importance of accessing the evolution of the structure deformation

during the impact phase makes it necessary to apply advanced measurement techniques, i.e. digital photogrammetry (Ferrero et al. 2015a).
Finally, the most debatable question concerns the adequacy of EC7 partial factors to this type of problems (Bedi and Orr. 2014; Lamas et al. 2014). As it will become clear in the next Section, the determination of the action on the barrier is governed by volume and velocity of the representative block for rock fall events and density, velocity and flow thickness for debris flow phenomena. Classical geotechnical parameters used to characterize soil and rock (porosity, Atterberg limits, cohesion, friction angle) do not play a fundamental role in this type of problems. Moreover, by analysing Table 2, we realize that the fundamental parameters that lead these phenomena are completely missing and the EC7 never deals with these aspects.
In the following sections of the paper the two phenomena will be treated in relation to the EC7 principles in order to evaluate the real possibility to apply LSD to this kind of problems and how.

3. An attempt to apply LSD to rockfall phenomena

The considered case study is located in the Gran Paradiso Park area (Valsavaranche, Aosta, Italy). A detailed site characterization has been published in Ferrero et al. (2016b).
In Table 3 are listed the values of orientation and spacing obtained by the non-contact survey (Ferrero et al. 2015b). The results are presented using interval analyses due to the uncertainties related with orientation data. In fact, the uncertainty on orientation derives from both natural variability of the orientation of a discontinuity set (aleatory uncertainty) and the characteristics of the survey method (epistemic uncertainty). In particular, sources of errors in sampling are classified as:

- Sampling error;
- Estimation error;
- Measurement error.

These errors are essentially linked to the lack of knowledge (Baecher and Christian 2003), therefore innovative techniques, which allow one, for example, to investigate large portions of rock mass or portions of it otherwise difficult to approach, provoke a consequent decrease of the epistemic uncertainty (Guo and Du 2007; Bedi and Harrison 2013).
If the used DSM has a high quality and the orientation of discontinuities respect to the line of sight of the instrument (camera, laser scanner) is favourable, the epistemic uncertainty regarding the geometric characteristics of the rock mass decreases (Ferrero et al. 2009). Otherwise, such as in case of sub horizontal planes, a much higher epistemic variability would be expected if the shooting line is almost parallel to them. In any case, while the aleatory uncertainty cannot be reduced in any way since it is an intrinsic characteristic of the rock mass, the epistemic variability can be reduced by planning a proper survey in terms of point density and shooting positions.
The representative block volume can be evaluated with the following equation (Palmström, 1996):

$$V_B = \frac{S_1 \cdot S_2 \cdot S_3}{\sin\gamma_{12} \cdot \sin\gamma_{23} \cdot \sin\gamma_{13}} \quad (4)$$

where S_1, S_2, S_3 are the spacings of the three sets and $\gamma_{12}$is the angle between poles of sets 1 and 2 (similarly for γ_{13} and γ_{23}).
Starting from the detached blocks observed at the base of the site, a Monte Carlo simulation has been performed for determining the frequency distribution of the volume of rock blocks (Fig. 3), considering the blocks generated by sets (K1, K2, K3).
Using the block volume cumulative distribution generated, three design block volumes have been chosen in order to assess the impact energy upon the barrier. Values are respectively equal to 0.5, 1.2 and 15 m^3, corresponding to 30, 50 and 90% of the cumulative frequency (Fig. 4). The barrier has been located at the x coordinate equal to 57 m and its hypothesised resistance is 1000 kJ.
Concerning the choice of the design block, EC7 gives no thorough information: it is true that the characteristic volume should be defined as the 95% fractile value, but, in rockfall events this condition is very restrictive and improbable. In the normal practise, the designers choose the design block on the basis of engineering judgement and then multiply it by a coefficient derived from the volumetric survey accuracy (Peila and Ronco, 2009). It would also be useful to introduce an appropriate criterion for the choice of Representative Elementary Volume (REV), finding a good compromise between plausible block dimensions and appropriate probability of failure.
Considering the three design block volumes previously mentioned, total kinetic energy has been evaluated by using the lumped-mass code RocFall (Rocsciences Inc.).
The kinetic energy values obtained from the three different rock blocks follow a Gamma distribution. Figure 4 shows the cumulative distribution of total kinetic energy of the blocks evaluated at the barrier position: this graph allows one to determine the probability of exceeding the barrier resistance (1-P(x))

considering different representative block volumes. Obviously, if the block dimension increases, the probability of failure of the barrier increases. For the case study here shown, the probability of failure varies between 0.12% and 89.38% for block volume equal to 0.5 and 15 m^3, respectively.

The described procedure is suitable for supporting the design of rockfall protection fences. Considering EC7, the Authors think that there are strong limitations in its application in this case: considering the table reporting the partial factors both for the actions and for the resistance (CEN 2004, Table A.4 and A.13 respectively), most of the factored parameters are not relevant for the design of these kinds of structures. With this example the Authors have emphasised that block volume is the most relevant parameter for a proper design, but unfortunately the code never deals with this aspect and no indication are given on the percentage of frequency to use or on which partial factor should be applied on a theoretical average block.

4. An attempt to apply LSD to debris flow phenomena

A LSD analysis was conducted on a hypothetical flexible barrier exposed to a debris flow phenomenon. The adopted calculation method is described in Brighenti et al. (2013); the suggested method allows one to evaluate the components of the force acting on cables and the maximum displacement during the filling of a barrier. The load is considered as the sum of a dynamic (q_d) and a static (q_s) component as described in the following equations:

$$q_d = \alpha \cdot \rho_f \cdot v_f^2 \quad (5)$$

$$q_s = k \cdot [h_f + h(t) - z] \cdot \rho_f \cdot g \quad (6)$$

where α is the dynamic coefficient, ρ_f the density of the debris in kg/m^3, v_f is the flow velocity in m/s, k the earth pressure coefficient, g the acceleration gravity in m/s^2; z the vertical position of the considered point, h_f the flow thickness (in meters), $h(t) = \sqrt{2 \cdot v_f \cdot t \cdot h_f \cdot \tan i}$, i is the inclination of the slope (in decimal degrees).

Regarding the dynamic coefficient, this value has been chosen equal to 2 for this type of barrier, in accordance with Canelli et al. (2012).

Taking into consideration the variability of v_f, h_f and k (as treated in Section 2), an interval analysis was performed (Moore et al, 1966). Concerning debris flow phenomena, the availability of data is inadequate: data from real events are not many; on the other hand, data from experimental tests are copious but affected by scale factors. As a consequence, the available databases come from back analysis of single events, randomly collected and, often, comparing phenomena from different geological domains. Thus, the nature of these parameters is epistemic and, consequently, the use of statistical methods to analyse these phenomena is affected by limitations. In brief, for any given amount of knowledge – and hence degree of uncertainty – there is an optimal statistical model that should be applied (Harrison, 2014). Thus, an interval analysis was performed and, for each parameter, a lower and an upper limit value were chosen. All the arithmetical operations required to analyse intervals were performed by considering all the possible combinations of the involved parameters.

The hypothesized barrier has a rectangular shape and is composed of 6 equally spaced cables, with a diameter equal to 24 mm (section 6*19S-FC) and belonging to the resistance class of 1770 N/mm^2, supporting a flexible net. The UNI EN 1023854 suggests a maximum load of 363 kN for this type of cables. On each cable a brake system is installed; the activation force of the brakes is 70 kN with a maximum elongation of 0.8 m.

All the described parameters are summarized in Table 4.

The analysis was performed following the three DA described in Section 2 and applying the partial factors listed in Table 2; furthermore, according to interval analysis principles, the evaluation of the load acting on the cables was calculated for each limit value. This procedure allowed one to check if Equation 1 was verified for each cable.

4.1 Design Approach 1 - Combination 1

In DA1 - C1 the forces evaluated with the calculation method proposed by Brighenti et al. (2013) were multiplied by 1.5 (variable and unfavourable action). As it was expected, using lower limits of velocity, thickness and earth pressure coefficient (respectively, 8 m/s, 0.3 m and 0.25), all the cables were verified; on the other hand, for the upper limits set (respectively, 12 m/s, 1.2 m and 0.35), the condition forced by Equation 1 was not satisfied (Fig.5).

Thus, the most unfavourable condition was represented by maximum value of velocity, thickness and earth coefficient (even if there was no sensible variation of the results changing the earth coefficient). Now, a question arises about whether or not it is correct to choose the maximum h_f and v_f values, since it is not predictable to have simultaneously maximum velocity and maximum flow height. By analysing experimental tests, an inverse proportionality between velocity and flow height has been observed (Hubl et al. 2009; Vagnon and Segalini 2016): if the velocity is high, the flow thickness is relatively small and vice versa. This linear dependence is clearly shown in Fig. 6 where velocity is expressed using Froude number,

Fr, (ratio between velocity and root square of gravity and flow thickness) and flow thickness as filling ratio, n (ratio between height barrier and flow height). Thus the condition depicted above is very precautionary, but also very improbable.
Furthermore, a last question arises: when considering the variability of parameters (v_f, h_f and k), is γ_Q sufficient/correct?

4.2 Design Approach 1 - Combination 2

This DA requires to increase the action (γ_Q = 1.3) and decrease the geotechnical parameters. In this case, since in EC7 there is no indication about the possibility to apply partial factors to velocity and thickness, the only geotechnical parameters are flow density (γ_γ = 1) and internal friction angle of the material (γ_{φ}' = 1.25).
Actually, for this type of geotechnical problems, this combination does not have a relevant significance or, better, it will be relevant if some partial factors were used to increase flow velocity and flow density.

4.3 Design Approach 2

For debris flow flexible barriers the DA2 is the most conservative (Fig.7): in fact, using both lower limits and upper limits, cables are never verified (except for cable 1).
A deep consideration should be done on the application of partial factor to resistance: in this problem, the resistance is the maximum admissible force of the cables. Since these cables are made of steel, it is excessive to apply reducing factor because the UNI EN 1023854 already provides a value with an appropriate safety degree.

4.4 Design Approach 3

The same considerations made for DA1 – C2 can be extended for this case (Fig.8). The Authors want to remark that application of partial factors to classical geotechnical parameters, in this type of problem, is not useful. In debris flow, where the effects on structures are governed by flow characteristics, the epistemic uncertainty correlated to these parameters shall be taken into account.

Conclusions

The aim of this paper is to evaluate the possible application of a partial factor approach, as the one proposed in the EC7, to the design of rockfall and debris flow flexible barriers.
With regard to rockfall, a main point is the evaluation of the design energy that is strictly connected to the representative block. The EC7 does not give indication about the analysis of the main ruling parameters (block volume and velocity) even if, as it has been shown in the paper, the availability of a great amount of data, thanks to non-contact surveys, allows one to obtain reliable statistical distribution of block volumes and consequently to define the probability of failure connected with the design block.
Regarding debris flow the issues increase: the application of flexible barriers as countermeasures is relatively recent and many questions are still open. The impact analysis for debris flow is considerably more difficult than that of rock fall and the structural design should be carried out starting from an accurate geological and geomorphological characterization of the basin (Vagnon et al., 2015a; Vagnon et al. 2015b). The use of an adequate flow calculation code is necessary in order to define the dimension of the event (detachment, flow path, impact velocity, depth of surge, mobilized volume). Evaluation of the impact force is strongly influenced by velocity and thickness; these parameters indirectly include information on volume, location of the barrier and basin characteristics that are subjected to many uncertainties. A satisfying “engineering criterion” to choose the best velocity and thickness combination should be found (i.e. the maximum?, a percentage of the maximum?) since the simultaneous occurrence of the most precautionary ones is very improbable.
As a consequence, a partial factor approach should factorise the main design features for these phenomena: block volume and velocity for rockfall and flow velocity and thickness for debris flow.
Apropos of debris flows, the Authors want to remark the fact that:
1- DA1 - C1 (actions are multiplied by the factor): since the actions depend on both velocity and flow thickness andthese parameters are linearly dependent, to consider the contemporaneous maximum height and velocity is too conservative.
2- DA3 and DA1 - C2 have not relevant meaning since the application of partial factors is made only on flow density and internal friction angle and not on the leading parameters (velocity and flow thickness); furthermore, reducing the resistance parameters of the flow is not correct because it would change the nature of the debris and consequently its rheology.
3- DA2 is the most conservative one: the Authors think that the application of partial factors on the steel structures is too restrictive since the values are already furnished with a certain safety degree. It is necessary to underline that all the regulations related to rockfall (ETAG27) and debris flow (EAD 340020-00-0106, forthcoming) are referred to the determination and certification of the resistance capability of the

retaining kit. Thus, the further application of reduction coefficients on the resistance of the structures appears redundant.
Currently, an analysis in the framework of LSD is not applicable since the partial safety factor set proposed does not cover the leading parameters of these phenomena In any case Partial factor method could only be applied for a few simple cases. All structure interaction problems like the ones proposed in this paper should be better analysed with the "first order reliability method" (FORM) (Callisto, 2010).
The probability of failure associated with the degree of uncertainty connected with these kind of structures has never been investigated, too. Reliability analysis like the one proposed in EN 1990 could be a future research development for an efficient structural design of flexible barriers.

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Tables

Table 1. Recommended minimum values for reliability index β (Eurocode 0, CEN 2001).

Reliability Class	Minimum values for β	
	1 year reference period	50 years reference period
RC3	5,2	4,3
RC2	4,7	3,8
RC1	4,2	3,3

Table 2. Partial factors on actions (or effect of actions), on soil parameters and on resistances for slopes and overall stability.

Table 1. Recommended minimum values for reliability index β (Eurocode 0, CEN 2001).

Action (A)		Symbol	Set A1	A2
Permanent	Unfavourable	γ_G	1.35	1
	Favourable		1	1
Variable	Unfavourable	γ_Q	1.5	1.3
	Favourable		0	0
Soil parameters (M)		**Symbol**	**Set M1**	**M2**
Angle of shearing resistance		$\gamma_{\varphi'}$	1	1.25
Effective cohesion		$\gamma_{c'}$	1	1.25
Undrained shear strength		γ_{cu}	1	1.4
Unconfined strength		γ_{qu}	1	1.4
Weight density		γ_{γ}	1	1
Resistance (R)	**Symbol**	**Set R1**	**R2**	**R3**
Earth resistance	$\gamma_{R;e}$	1	1.1	1

Table 3. Orientation and spacing values from non-contact survey

	Dip [°]	Dip Direction [°]	Spacing [m]
K1	[70;80]	[76;90]	[0.2;5]
K2	[40;60]	[210;250]	[0.8;15]
K3	[75;85]	[316;336]	[0.3;7.4]
KS	[32;42]	[310;330]	[0.1;0.9]

Table 4. Barrier, flow and basin data used in the calculation method developed by Brighenti et al. (2013)

Barrier data	
L_B [m]	6
H_B [m]	5
n° cables [-]	6
p [m]	1
φ [mm]	24

E_{steel} [kPa]	2.1E+11
L_{break} [m]	0.8
$F_{activation\ break}$ [kN]	70
Flow data	
ρ [kg/m^3]	1850
v_f [m/s]	8 - 12
h_f[m]	0.3 - 1.2
α [-]	2
k [-]	0.25 - 0.35
Basin data	
B [m]	6
i [°]	35

Figure Captions

Fig. 1 Schematization of the EC7 limit states design: probability distribution of the actions and material resistance (Bedy and Orr 2014)

Fig. 2 Net barriers against rock fall risk after construction (a) and after impact (b). Debris flow flexible net barrier installed in a natural channel (c). Net barrier filled with debris after a debris flow event (d)

Fig. 3 Cumulative distribution of the detached block volumes and estimated block volume using the Monte Carlo simulation

Fig. 4 Cumulative distribution of total kinetic energy evaluated considering three different volume blocks. The graph is useful to estimate the probability of exceeding the barrier resistance (1000 kJ) in function of REV

Fig. 5 Maximum force acting on each cables evaluated in according to A1 - C1: green line represents the maximum admissible force, red square dots represent force values calculated using upper limits coming from interval analysis and blue diamond dot using lower limits

Fig. 6 Linear correlation (correlation coefficient equal to 0.92) between filling ratio, n (ratio between height barrier and flow height) and Froude number of the current, Fr, from experimental tests

Fig.7 Maximum force acting on each cable evaluated according to A2: green line represents the maximum admissible force, red square dots represent force values evaluated using upper limits coming from interval analysis and blue diamond dot using lower limits

Fig. 8 Maximum force acting on each cable evaluated according to A3: green line represents the maximum admissible force, red square dots represent force values evaluated using upper limits coming from interval analysis and blue diamond dot using lower limits

Fig1

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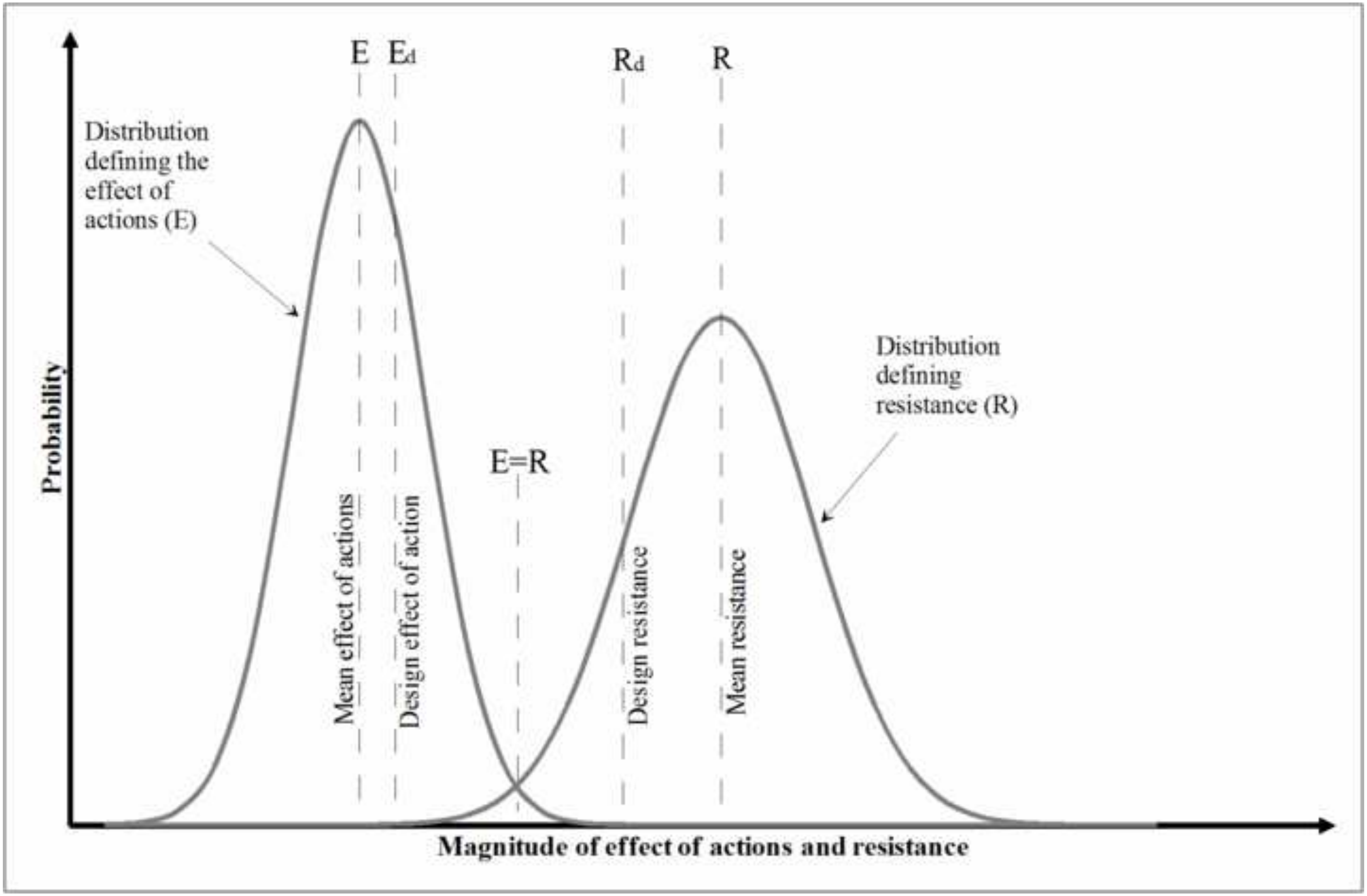

Fig2

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Fig3

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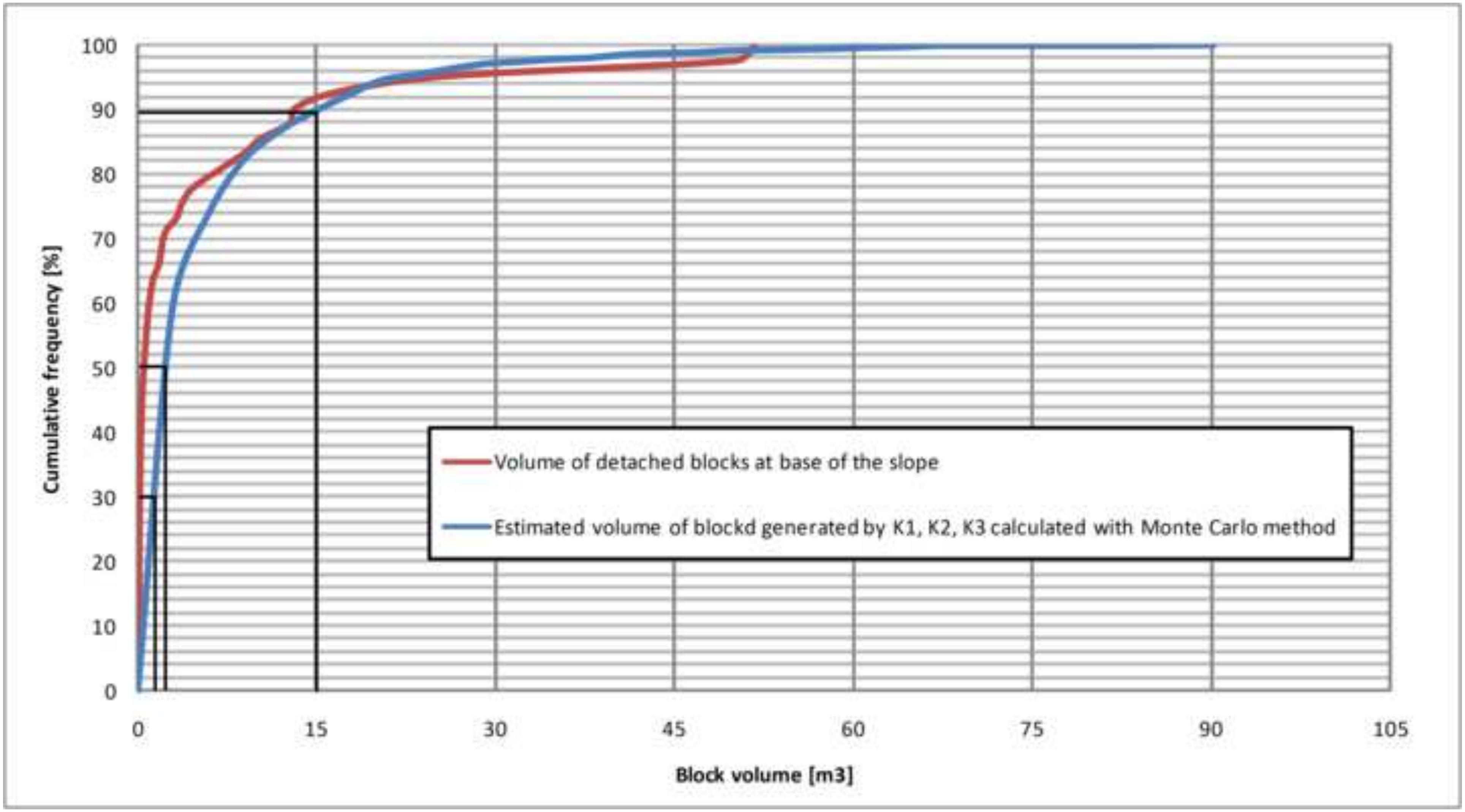

Fig4

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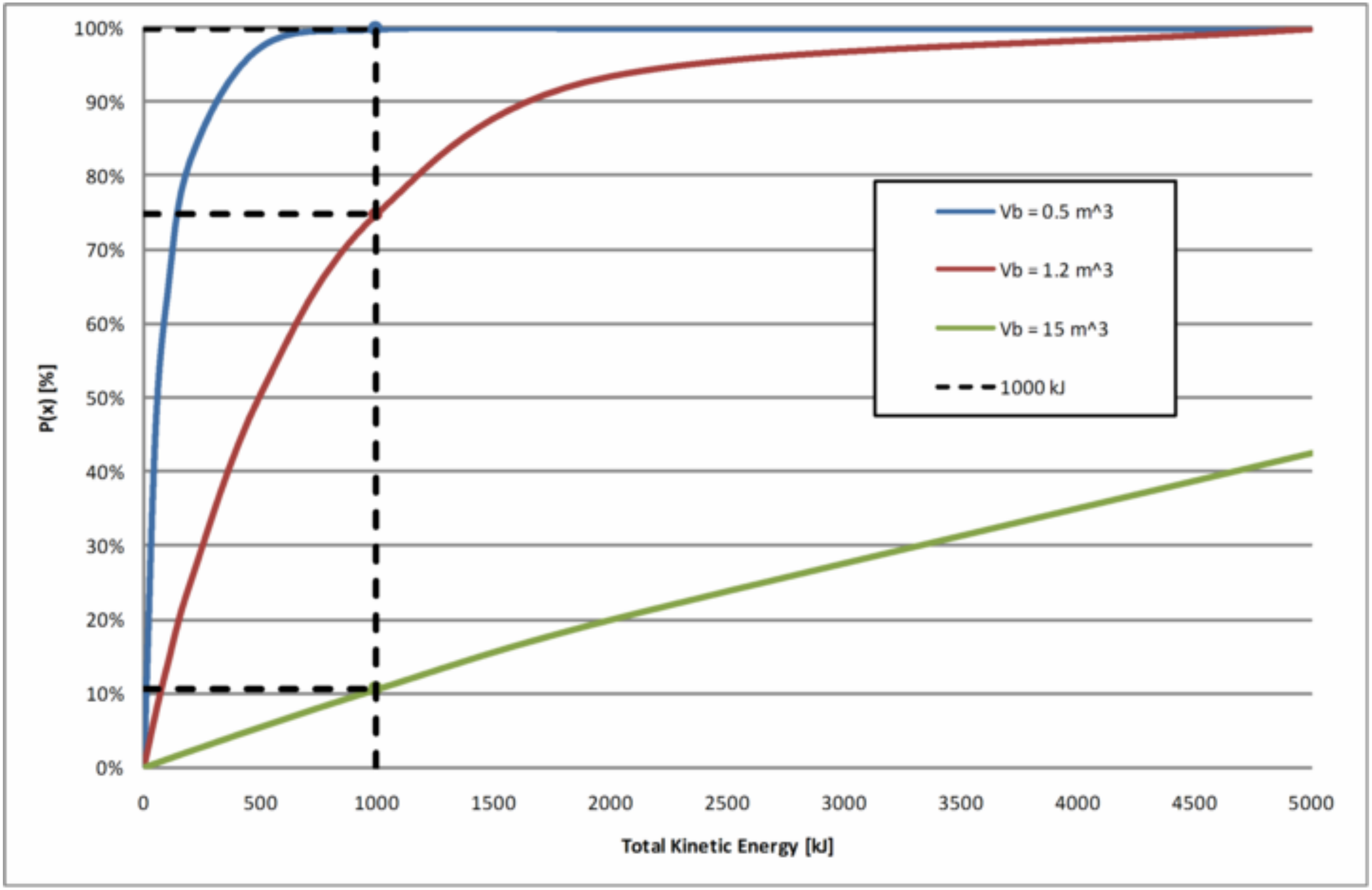

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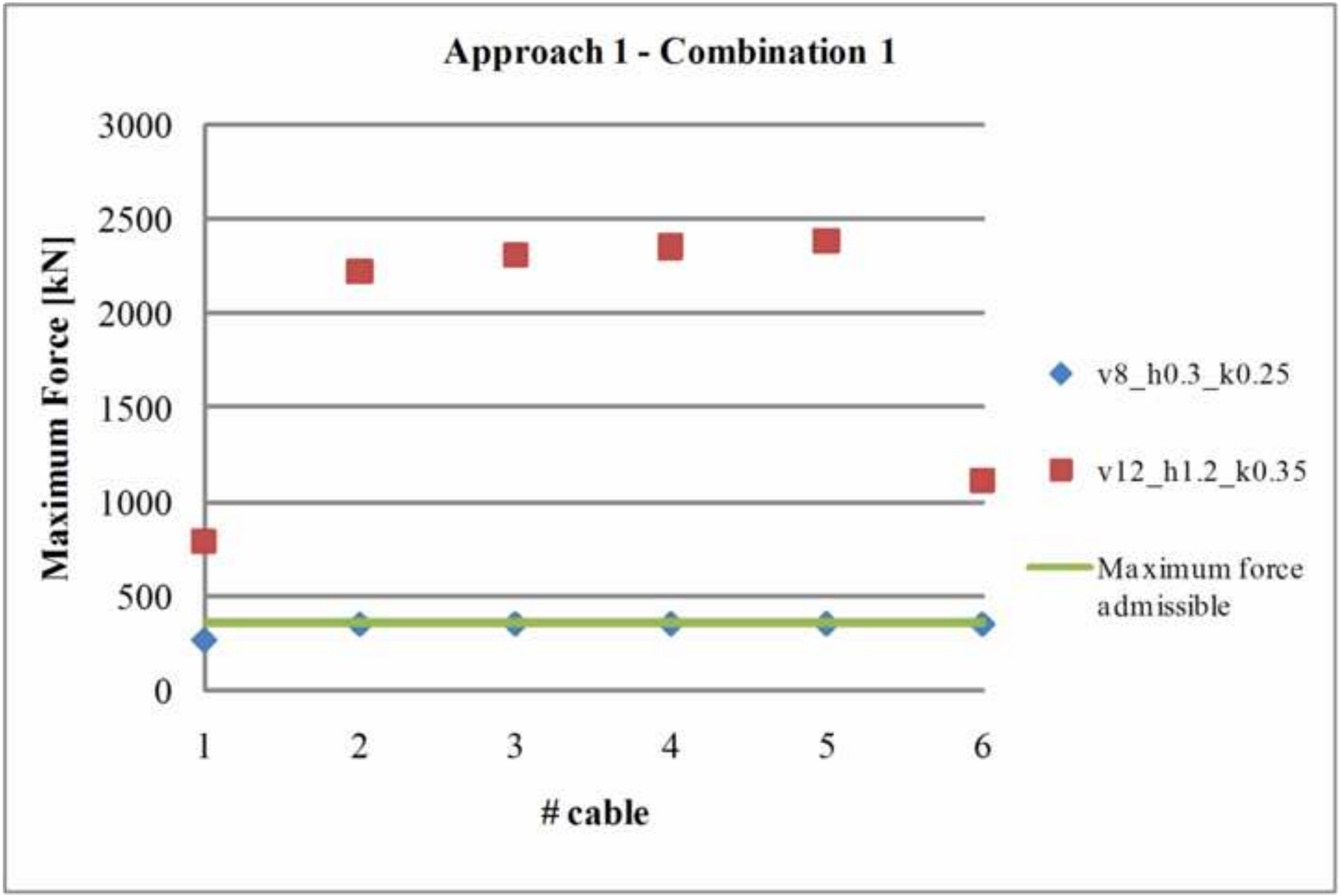

Fig6

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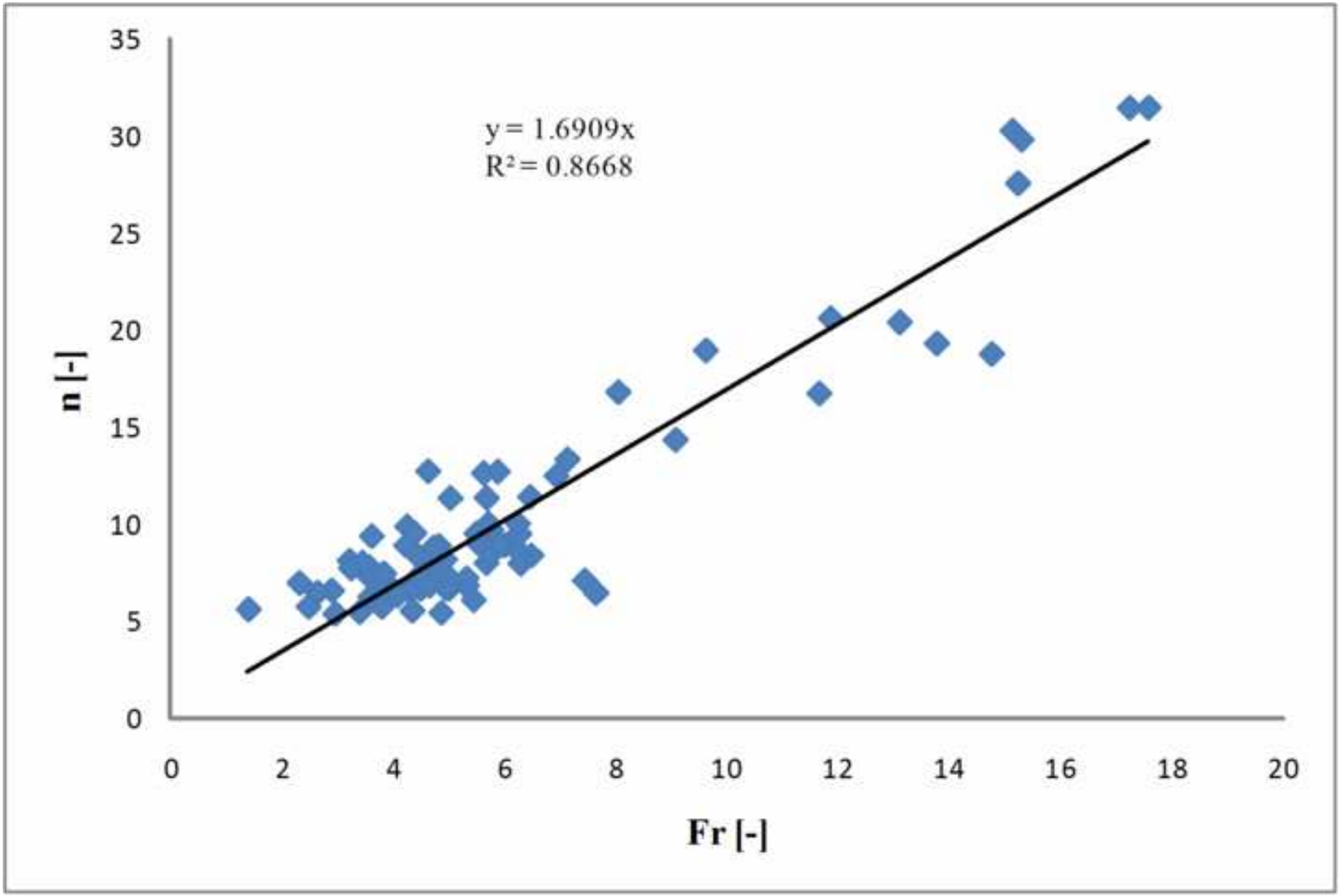

Fig7

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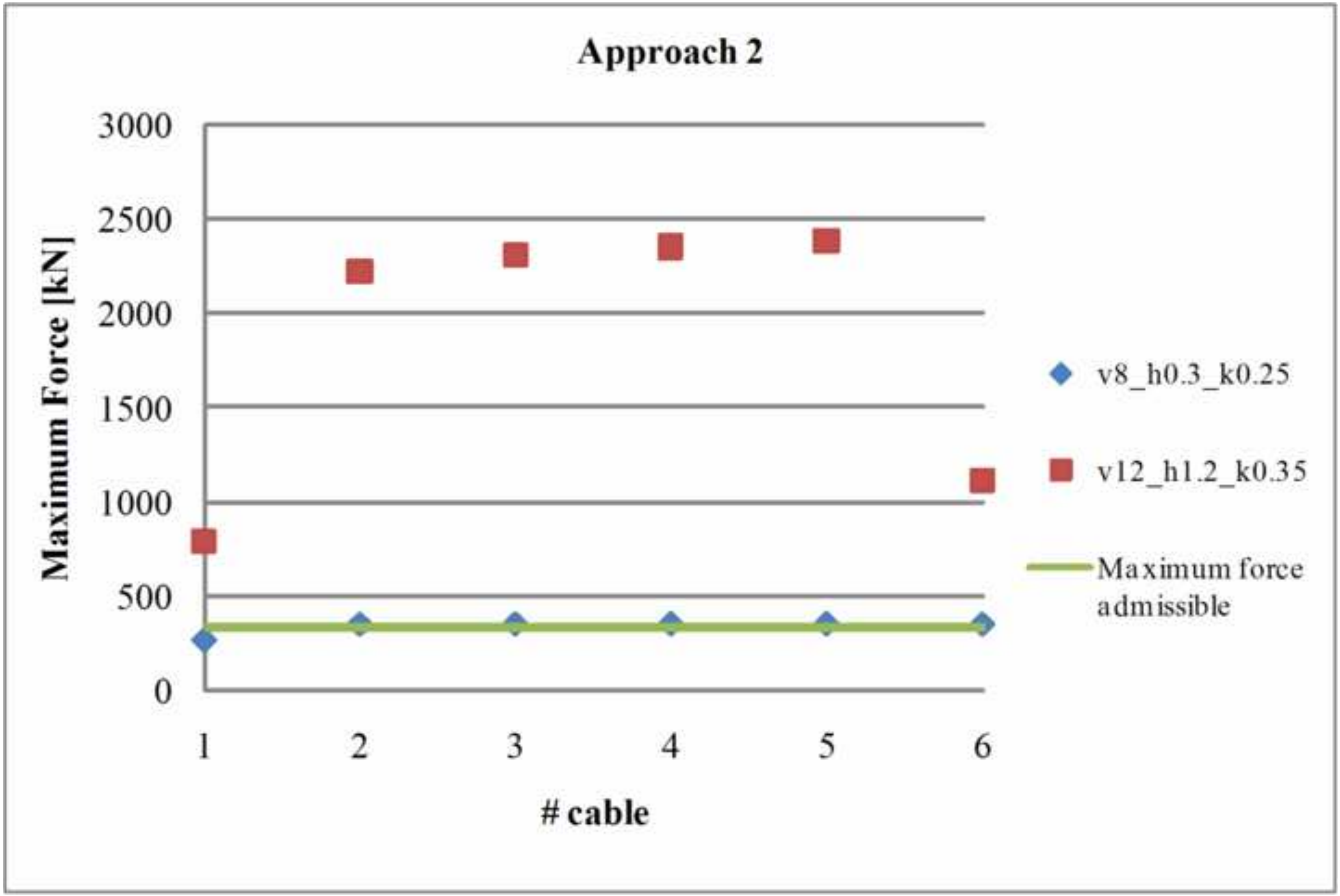

Fig8

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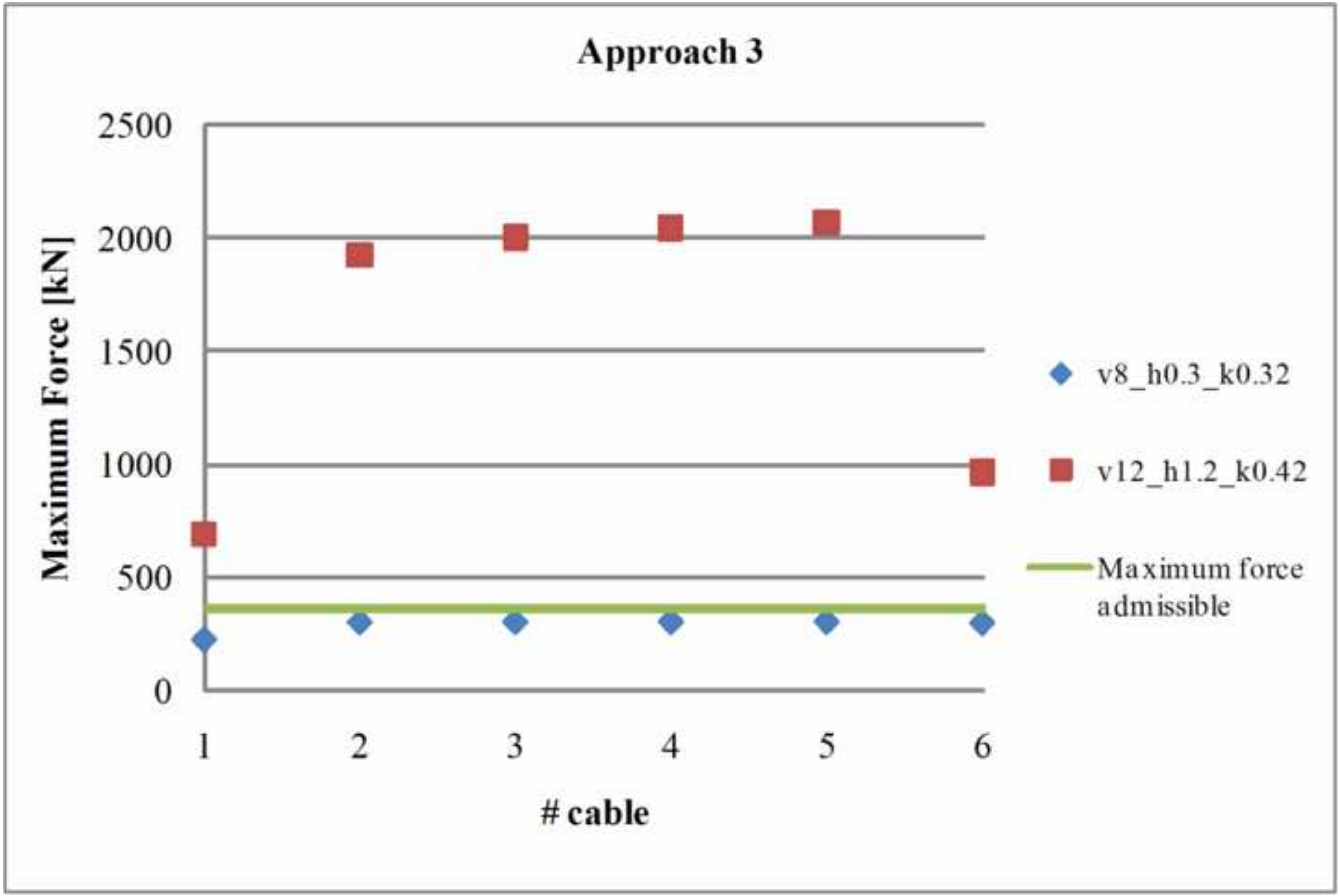

COMMENTS TO THE AUTHOR:

Reviewer #1:

In this manuscript, the authors propose an analysis in the framework of EC7 for rockfall and debris flow phenomena, trying to evaluate the possibility to apply a partial factors approach for these particular slope movements. The work is based on the application of EC7 to two case histories one of rock fall and one of debris flow respectively. The case histories are well documented and properly developed according to all phases from rock mass characterization to the block path or flow runout evaluation.

Eventually, the authors conclude that the set of partial factors presented in EC7 is incomplete for these kinds of applications, since many important parameters related to rock and soil mechanics are not considered and that a complete reliability analysis that takes uncertainties into account is extremely convenient to quantify the failure probability of these kinds of structures.

The obtained results are sound and convincing and consistent with the applied methodology. The paper is interesting for the scientific community since no guidelines are available for the design of flexible barriers.

To the best, knowledge of this reviewer, the topic of this paper is overall within the major scopes of the journal and may be of some interests to its general readers and, in particular, those specialized in civil and environmental engineering. The manuscript can be considered for publication with minor revisions. It is recommended that the Authors consider the following points for clarification and completeness before publication:

Page 2
Line 21 - The percentage of 0.0072% refers to a uniform probability of failure for a 50 year reference period and for a RC2 reliability class, as listed in Table B2 EN 1990:2002. It would be better to change that value introducing the cited table.
We added the following statement and the required table:
"The structures are classified into three main reliability classes (Table 1), assuming different reliability targets and consequently different probability of failure"

Line 29 - Introduce abbreviation "DA" after design approach
Done.

Page 3
Line 13 - It is not clear for this reviewer the meaning of "stress analysis is suggested". Please, give more details about it. Revise that paragraph.
We modified the paragraph and added the following sentences to better explain the concept:
"In particular, the force approach allows us to consider both the dynamic and static effects of the impacting front on the barrier. Moreover, all the involved parameters in the impact phase (particularly velocity and flow thickness) show marked time dependence: consequently energetic approaches cannot take into account this evidence that is better simulated using force approaches."

Lines 25 to28: this reviewer think that this paragraph is unnecessary.
The paragraph has been deleted.

Line 35: Explain the meaning of "reliability target".
We added the following sentences:
“The reliability target is assigned in function of the importance of the designed structure and the reference period of 1 year or 50 years. In brief, the reliability target corresponds to levels of safety of the structures and it is related to the associated probability of failure. In particular the probability of failure is expressed through a performance function that for each geotechnical design situation is:”

Line 60: delete Design Approach. Use abbreviation.
Done.

Page 5
Line 13: better explain the meaning of aleatory and epistemic uncertainties
We added the following sentences:
“In particular, sources of errors in sampling are classified as:
- Sampling error;
- Estimation error;
- Measurement error.

These errors are essentially linked to the lack of knowledge (Baecher and Christian 2003), therefore innovative techniques, which allow one, for example, to investigate large portions of rock mass or portions of it otherwise difficult to approach, provoke a consequent decrease of the epistemic uncertainty (Guo and Du 2007; Bedi and Harrison 2013).”

Page 6
Line 9-12 Better explain the use and reason of interval analysis
We added the following paragraph:
“Concerning debris flow phenomena, the availability of data is inadequate: data from real events are not many; on the other hand, data from experimental test are copious but affected by scale factors. As a consequence, the available databases come from back analysis of single events, randomly collected and, often, comparing phenomena from different geological domain. Thus, the nature of these parameters is epistemic and, consequently, the use of statistical methods to analyse these phenomena is affected by limitations. In brief, for any given amount of knowledge – and hence degree of uncertainty – there is an optimal statistical model that should be applied (Harrison, 2014). Thus, an interval analysis was performed and for each parameter, a lower and an upper limit value were chosen. All the arithmetical operations required to analyse intervals were performed by considering all the possible combinations of the involved parameters.”

Even if the paper is well written, the manuscript will largely benefit from polishing the English.
Done.