A time-independent reliability based design approach for debris flow flexible barriers

A time-independent reliability based design approach for debris flow flexible barriers

Maddalena Marchelli[1*] and *Chiara* Deangeli[1]

[1]DIATI, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy

Abstract. The design of debris flow protective structures has represented a challenge since the last decades. The design process might consider several variables related to actions and resistances, mainly linked to impact pressure and dynamic pressure resistance. Debris flow events do not have always the same magnitude, and small events can occur with a high probability. Therefore, an events frequency-magnitude relationship might be considered in the design of protective structures. In the Eurocodes framework, the fixed partial safety factors design approach not considering the intrinsic site variability of these phenomena, does not allow obtaining a specific probability of failure. Reliability-based approaches reveal to be compelling solutions. Focusing on flexible barriers, the paper presents a novel time-independent reliability approach, which considers all the possible debris flow events and provides the failure probability of a barrier in a given temporal interval.

1 Introduction

Debris flows are one of the most hazardous natural phenomena, due to their unpredictability, and high velocities. These processes, constitute a serious threat to life, properties and infrastructures [1]. Consequently, debris flow risk reduction represents a significant aspect in risk management policies.

Debris flow flexible barriers are effective protective measures, due both to the ease of transport and installation [2]. These barriers mainly involve a combination of steel ropes and nets consisting in high-tensile wire in steel, whose assembling and components technologies are constantly evolving [3] (Fig. 1).

As structural works made as kits, their performances have to be assessed in relation to their essential characteristic, i.e. the dynamic impact pressure resistance, the height and the maximum deformation. A European guideline introducing codified methods for assessing such devices has been developed in 2016, i.e. EAD 340020000106 [4]. In the framework of Eurocodes [5, 6], it should be verified that:

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

where E_d, R_d are the design values of the effects of the actions and of the resistances, respectively. Providing that Eqn. (1) is satisfied, the current design procedure consists in choosing a suitable product, and, thus, resistances coincide with performances, while actions can be obtained by both codified tests or advanced numerical modelling. The considered actions are those related to the impact pressure exerted by the flow, whose design value should be accurately evaluated through investigations on past events and trustworthy analytical or numerical debris-flow dynamic analyses [7]. Nevertheless, modelling these unsteady phenomena is very difficult, as they are characterized by entrainment and deposition during their path, exhibiting also grain-size segregation, excess of water pressure, whose extent is generally difficult to measure. Moreover, transition from sliding to flow might occur during the motion [8-11]. Consequently, the generally adopted models adopt several simplifications. Additionally, in the same site events can differ one from another and smaller events occur with a higher frequency.

In the framework of limit state design with partial safety factors approach, no specifications on both characteristic values and partial safety factors are present in the Eurocodes [12] referring to debris flows barrier. Due to the large variability in the statistics related to actions, the choice of a unique, i.e. fixed, value for each safety factors is not suitable, as fixed factors not allow obtaining a specific probability of failure. Specific parametric studies devoted to define a possible non-site-specific range of factors for obtaining a target failure probability in a given time are still missing.

Consequently, assuming that the failure of the system occurs for debris flow pressure exceeding the resistance of the barrier, the present work aims at identifying a solution for the design of such system, based on the reliability approach (Eurocode 0 [5]). The profitability of such kind of approach was highlighted by [12], in which a general framework is provided. Nevertheless, the time-variant reliability issues have not been tackled yet, e.g. magnitude-frequency relationship of the possible events and their consequences have not been considered. Addressing these issues, following the

* Corresponding author: maddalena.marchelli@polito.it

general suggestions provided by ISO 2394 [13], the Authors propose a methodology, mimicking a method defined for rockfall flexible barriers [14-16], considering that:

(i) the probability of failure, i.e. the probability of having actions larger than the resistances, should be defined for a specific time period;
(ii) actions can vary during the event and, most importantly, their maxima vary from one event to another. A frequency-magnitude relationship for the maximum action should be evaluated and an integration over time of the actions should be considered in the design process.

The proposed methodology is delineated in Sec. 2, while its limitations and advantages are discussed in Sec. 3. Finally, conclusions and future perspective are outlined.

Fig. 1 Debris flow flexible barrier (Courtesy of Geobrugg Italia)

2 Methodology

This section provides the fundamental principles of the time-independent reliability approach adopted for debris flow protection structures. Debris flow flexible barriers have to retain the solid phase of the debris flow mixture, resisting the dynamic pressure exerted by the flow, without exceedingly deforming, breaking, or collapsing. The height of the flow is generally assumed to be comparable with the channel height. Therefore, the failure mode of such barriers can be simplified into a failure process related to exceeding pressure, when the dynamic pressure resistance p_B, is lower than the flow pressure. The resistance p_B is evaluated with the assessment procedure of [4], i.e. with either standardized field test or numerical analysis. The boundary between failure and safety can be mathematically described through a limit state function that allows obtaining the design values (subscript $_d$) of the variables. Vice-versa, if the effects of the actions are known, the limit state function enables to assess the reliability of the protection structure.

Going deeply into the reliability approach, the probability of failure p_f, in a given period τ (in years), can be computed as:

$$p_f(\tau) = 1 - e^{-\nu\tau p_{f,a}} \tag{2}$$

where ν is the mean expected annual frequency of a debris flow of any size, while $p_{f,a}$ is the probability of failure if a debris flow impacts against the barrier, i.e. considering the certain occurrence of debris flow events. As other natural phenomena, small events can occur with a higher probability than huge ones [14].

This means that the effects of the actions are time-dependent, i.e. for a given return period *T*, a pressure *p(T)* can be defined. The design method herein proposed computes the failure of the barrier considering all the possible events that can occur at any time, and, for this reason, can be considered as "time-independent".

Another consideration relates to the pressure, which, during each event, is not a deterministic value but can be described as a probabilistic function, whose reference, i.e. characteristic value, is p_k.

Consequently, $p_{f,a}$, can be obtained through:

$$p_{f,a} = \int_0^{\infty} p_f \,|(p_k = \pi) f_{p_k}(\pi) d\pi \tag{3}$$

being $p_f|(p_k = \pi)$ the probability of failure if the pressure p has its characteristic value p_k equal to π, i.e. a random variable through which the characteristic value p_k is defined, and $f_{p_k}(\pi)$ the probability density function related to each pressure distribution, whose characteristic value is π. The integral is calculated over all the possible impact pressures, to provide the time-independency of the method. It should be stated that the probability $f_{p_k}(\pi)$ is difficult to be obtained. Providing that $\int_{-\infty}^{\infty} f_{p_k}(\pi)\, d\pi$ is equal to 1, Hong et al. [17], based on a large set of measurements on real phenomena, suggest to assume a Weibull distribution. It means that:

$$f_{p_k}(\pi) = \frac{k}{\mu}\left(\frac{\pi}{\mu}\right)^{k-1} e^{-(\pi/\mu)^k} \tag{4}$$

where k and μ are coefficient that should be properly calibrated (Fig. 2a). Obviously, Eqn. (4) holds for $\pi \geq 0$. The conditional failure probability $p_f|(p_k = \pi)$ is studied through a state function, which describes both safe and unsafe barrier conditions, accounting for the resistance p_B .The state function $G(\mathbf{p})$ can be defined as:

$$G(\mathbf{p}) = G\begin{pmatrix} p \\ p_B \end{pmatrix} = p_B - p \tag{5}$$

where p is the flow pressure, described as a probabilistic variable, as stated before (Fig. 2b).

The failure probability, for each event, is computed as:

$$p_f|(p_k = \pi) = P(G(\mathbf{p}) \leq 0) = \iint_{G(\mathbf{p})\leq 0} f_G|(p_k = \pi)(\mathbf{p}) dp_B dp \tag{6}$$

where f_G is the probability density function of the difference between barrier resistance and debris-flow impact pressure, provided that p_k is equal to π.

3 Discussion

This section deals with (i) the probability distributions in time of the relevant variables and (ii) the capability of the method to be used for deriving reliable partial safety factors that can, thus, be adopted in a semi-probabilistic design approach. In this last case, a debris flow event with a given return period is considered for the design actions.

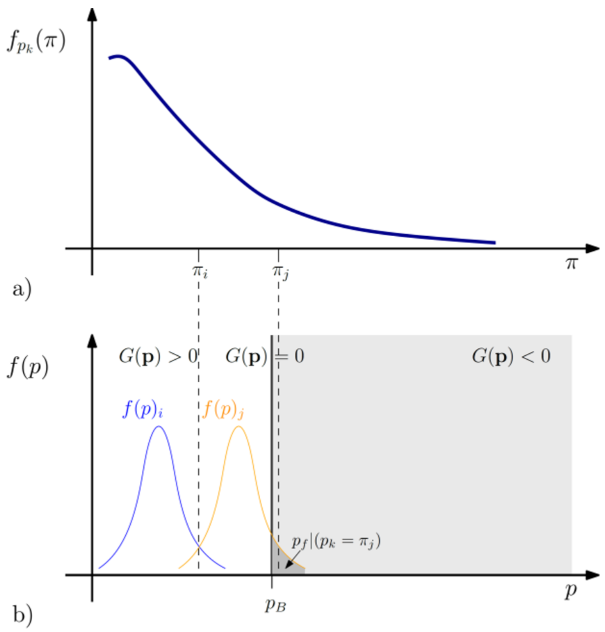

Fig. 2 Probability density function $f_{p_k}(\pi)$ related to any possible pressure distribution, whose characteristic value is π, described with a Weibull distribution (a); and probability density function of the pressure for different events (e.g. *i* and *j*, whose characteristic values are π_i and π_j, respectively) with both safe and unsafe conditions (b). The capacity of the barrier is assumed to be described by a Dirac-δ distribution.

3.1 Uncertainties related to the reliability approach

The proposed equations account for the most general situation, assuming to have a magnitude-frequency relationship based, e.g., on catalogue of recorded past events. The equations do not consider the method of calculation of the impact pressure p exerted by the flow. Several models have been developed to estimate a peak pressure value [18] based on a hydrodynamic approach or on a hydro-static approach [19,20]. In the hydrodynamic approach the impact pressure is computed through:

$$p = \rho v^2 \alpha \tag{7}$$

where ρ is the density of the debris flow mixture, , v is the velocity of the fluid, and α a dynamic coefficient, which depends on the grain size distribution, and, thus, related to ρ itself. In the hydrostatic approach, the impact pressure can be evaluated using:

$$p = k_s \rho g h \tag{8}$$

where $k_s$is an empirical coefficient, g the gravity, and h the flow depth.
The impact pressure is thus described through other variables, i.e. ρ, v, h, each of which can be defined by a probability distribution. In this case, the state function should account for those variables, together with their joint probability density functions.

Taking the hydrodynamic formulation as an example, Eqn. (5) turns thus into:

$$G(\mathbf{p}) = G\begin{pmatrix} \rho \\ v \\ p_B \end{pmatrix} = p_B - \rho v^2 \alpha \tag{9}$$

and Eqn. (3) into:

$$p_{f,a} = \int_0^\infty p_f\,|(\rho_k = \delta \text{ and } v_k = \omega\,) f_{\rho_k v_k}(\delta,\omega) d\pi \tag{10}$$

being $f_{\rho_k v_k}$ the joint probability density function of the characteristic values of debris density and velocity, defined through the random variables δ and ω, respectively (Fig. 3). It is worth mentioning that time-dependent probabilistic distributions of each variable are very difficult to achieve, as well as the assessment of the goodness of the existing predicting impact models, as shown in [12].

Another important issue concerns the distribution of the dynamic pressure resistance of the barrier and its characteristic value. Unfortunately, this information can be obtained only for products verified with advanced numerical tests [21]. As the design of such systems is based on the choice of proper flexible kits among those available on the market, a Dirac-δ distribution, at the maximum tested value according to [4], can be used.

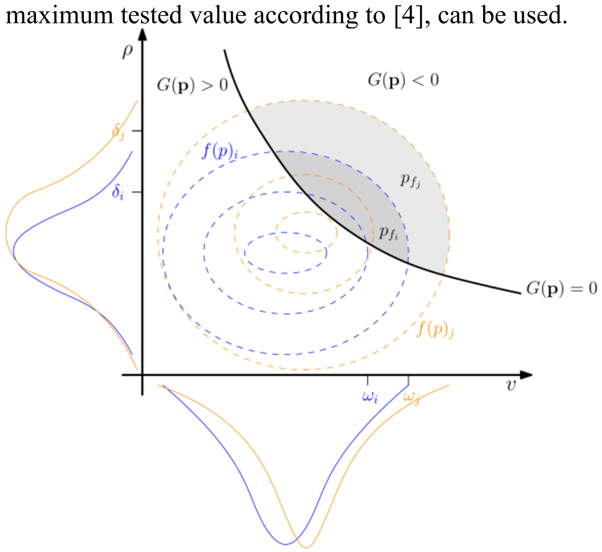

Fig. 3 Probability density functions of $\boldsymbol{\rho}$ and $\boldsymbol{v}$ for different events (e.g. *i* and *j*, whose characteristic values are δ_i, ω_i and δ_j, ω_j, respectively) with both safe and unsafe conditions.

3.2 Capabilities of the method: derivation of the partial safety factors

The proposed time-independent reliability approach allows obtaining a failure probability for a given protection system in a given period. Moreover, this method can be used to derive site-specific partial safety factors which, if adopted in a more straightforward semi-probabilistic design framework [5,6], guarantee to obtain a given failure probability. Unlike structural engineering, in geotechnical engineering the actions are very site-specific and, consequently, the use of a fixed value for each factor entails a non-unique value of failure probability. In the partial safety factor approach, only a characteristic value of the impact pressure, associated to a specific return period, should be considered. The reference return period T can be 100 years or more. For a given T, the characteristic pressure becomes:

$$p_k(T) = -\mu \left[\ln\left(\frac{1}{\lambda T}\right)\right]^{1/k} \quad (10)$$

Hence, given a specific $p_f(\tau)$, with the pressure probability distribution of the specific site, the minimum required $p_{B,min}$ is computed. The partial safety factor for the pressure γ_p can thus be obtained as:

$$\gamma_p = \frac{p_{B,min}}{p_k(T)}. \quad (11)$$

Extending the study for different sites a possible range of γ_p can be obtained. Although there are no specific prescriptions on the allowable risk due to debris-flow, a one-year failure probability equal to value $p_f(1\text{yr}) = 10^{-5}$ can be adopted, which is coherent with the suggestions for rockfall barrier provided in the Italian Standard [22].

4 Conclusions

Flexible barriers are among the most adopted passive mitigation measures for debris flow. During the last decade, several technologies have been developed, resulting on very complex systems, whose essential characteristics should be assessed according to [4]. In this framework, the evaluation of the proper actions to consider in the design process represents a key aspect, nowadays still under debate. Today's regulation does not specifically deal with such structures. In the framework of the Eurocodes, a partial safety factors approach with fixed factors might not be trustworthy as it does not account for a specific failure probability, nor for the site-specificity of the problem. The profitability of reliability-based approaches has recently highlighted. Nevertheless, the variability in time of the input variables has not been considered yet.

The present paper proposes a novel reliability approach, which determines the failure probability of a given product during a specific temporal interval, accounting for all possible events, for which a frequency-magnitude relationship is defined. For this reason, the approach is time-integrated and can be defined as time-independent. Given a target failure probability, this method allows also to obtain site-specific partial safety factors to adopt in a semi-probabilistic approach.

Further developments could investigate more deeply the distributions of the input variable or the method could be extended also to rigid barriers [23,24] or even embankments [25].

References

1. M. Jakob, O. Hungr. *Debris-flow hazards and related phenomena*. Springer-Verlag, Berlin Heidelberg, **749,** (2005)
2. L. Canelli, A.M. Ferrero, M. Migliazza, A. Segalini, Nat. Hazards Earth Syst. Sci. **12**, 5 (2012)
3. C. Wendeler, V. Budimir, M. Denk, *Debris flow protection with flexible ring net barriers – 10 years of experience, in* Proceedings of the XVI Danube - European Conference on Geotechnical Engineering, 7-0 June 2018, Skopje, R. Macedonia (2018)
4. EAD 340020000106, Flexible kits for retaining debris flows and shallow landslides/open hill debris flows, EOTA (2016)
5. EN 1990:2002, Eurocode 0 - Basis of Structural Design (2002)
6. EN 1997–1:2004, Eurocode 7 - Geotechnical Design. Part 1: General Rules, (2004)
7. D.Tiranti, C. Deangeli, Front. Earth Sci., **3**, 8 (2015)
8. C. Deangeli, Rock Mech. Rock Eng., **41**, 1 (2008)
9. C. Deangeli, Am. J. Environ. Sci., **5**, 4 (2009)
10. C. Deangeli, D. Tiranti, F. Marco, M. Volpato, M. *Comparison of Debris Flow Depositional Scenarios Using Different DTMs, in* Engineering Geology for Society and Territory, Springer, **2,** 1667-1671 (2015)
11. C. Deangeli, Am. J. Environ. Sci., **3**, 3 (2007)
12. F. Vagnon, A.M. Ferrero, L.R. Alejano, Landslides, **17**, 49-59 (2020)
13. ISO 2394 :2015, General Principles on Reliability for Structures (2015)
14. V. De Biagi, M. Marchelli, D. Peila, Eng. Struct., **213**, 110553, (2020)
15. M. Marchelli, V. De Biagi, D. Peila, Int. J. Rock Mech. Min. Sci., **139** 104664 (2021)
16. M. Marchelli, V. De Biagi, D. Peila, Geosciences, **10**, 8 (2020)
17. Y. Hong, J.P. Wang, D.Q. Li, ZJ Cao, C.W.W. Ng, P. Cui, Eng. Geo., **187**, 122-134 (2015)
18. F. Vagnon, Landslides, **17**, 313-333 (2020)
19. A. Armanini. *On the dynamic impact of debris flows*, in Recent developments on debris flows. Lecture notes in Earth Sciences, **64**, 208-226 (1997)
20. J. Hübl, J. Suda, D. Proske, R. Kaitna, C. Scheidl. *Debris flow impact estimation*, in Proceedings of the 11th international symposium on water management and hydraulic engineering, Ohrid, Macedonia, **1**, 1-5 (2009)
21. D. Song, G.G.D. Zhou, M. Xu, C.E. Choi, S. Li, Y. Zheng, Eng Geol **251**, 81-92 (2019)
22. UNI 11211–5:2019. Opere di difesa dalla caduta massi - Parte 5: Ispezione, Monitoraggio, Manutenzione e ruolo dei Gestori, (2019)
23. M. Marchelli, V. De Biagi, Int. J. Prot. Struct. **10**(1), 116-131 (2019)
24. M. Marchelli, A. Leonardi, M. Pirulli, C. Scavia, Géotechnique, **70**(3), 226-237 (2020)
25. M. Marchelli, C. Deangeli, GEAM, **165**, 50-59 (2022)