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Rockfall mitigation using a new probabilistic technique in the Cavazzo lake area

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Abstract. A case history of rock slope engineering concerning design of control measures adopted to protect a down slope area from rockfall hazard is described below. The paper deals with the first practical application of design procedure RDBD (*Rockfall Defensive Barrier Design*), developed by the authors and based on a probabilistic approach both during rockfall simulation phase and during design phase regarding defensive works. The innovative aspect of the procedure consists in the undertaking of probabilistic parameters, the *Safety Levels*, as conditioning elements of the entire project development, opposed to the deterministic sizes which have been adopted till today in this geotechnical engineering field. As a result, a multiple defensive system has been developed step by step, ensuring the prefixed safety level on the analyzed risk area and avoiding any superfluous defenses or dangerous underassessment.

Keywords. Rockfalls, Beta Probabilistic Distribution, Defensive Barriers.

Introduction. Even if less spectacular than large landslides, small scale rockfalls and consequent block's motion along slopes are frequent in the Alpine area of North East Italy. These processes can be very dangerous because they could quickly impact upon transportation facilities and buildings, often with fatal results. Since mitigation of rockfall risk or maintenance of protective measures could involve considerable money investments and the natural phenomenon, although triggered by deterministic laws, is characterized by intrinsic randomness of parameters governing block's motion, in the author's opinion the design of defensive works could be based on a rational and probabilistic new approach. Each step of design development could be supported by probabilistic analysis,

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both during localization of risk and computer simulation of rockfalls, and adequate defensive measures assessment. With reference to simulation of block trajectories, the computer codes could implement probabilistic models using randomly generated values of characteristic geomechanical input parameters (restitution coefficient "e", rolling and sliding friction angles) within a defined variation range (Paronuzzi et al. 1999). Besides, design of protective defenses could involve reliability analysis using, for example, the Fault Tree Analysis or Event Tree Analysis (Paronuzzi et al. 1995, Ang et al. 1984).

The area of study is located at the base of Mount Naruint (Bordano, Italy), near the southern shore of Cavazzo Lake (Figure 1). As in that area human activities and a national

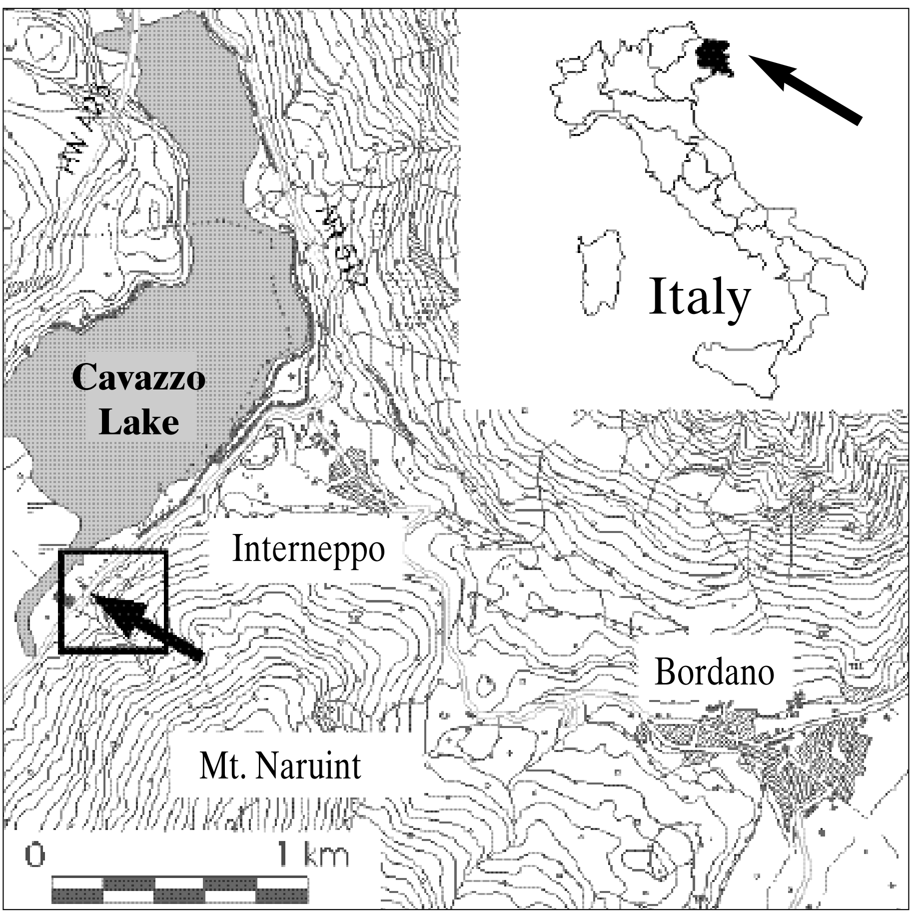

Figure 1. Location of the examined area.

road section are subject to rockfall risk, it has been possible to test the new design procedure. Below is a description of the procedure.

Materials, methods and results

The RDBD procedure. Design procedure RDBD (Rockfall Defensive Barrier Design) consists of several steps strictly connected and easily organized in a flow chart (Figure 2). It is based on a probabilistic approach both during analysis and design, taking probabilistic parameters, so-called "Safety Levels", as conditioning elements of the whole project development (Coccolo et al. 1998). As codified from RDBD, the first parameter to define is the *Required Safety Level* SL_{REQ}. It represents the "a priori" acceptable probability referred to a rockfall risk zone, depending

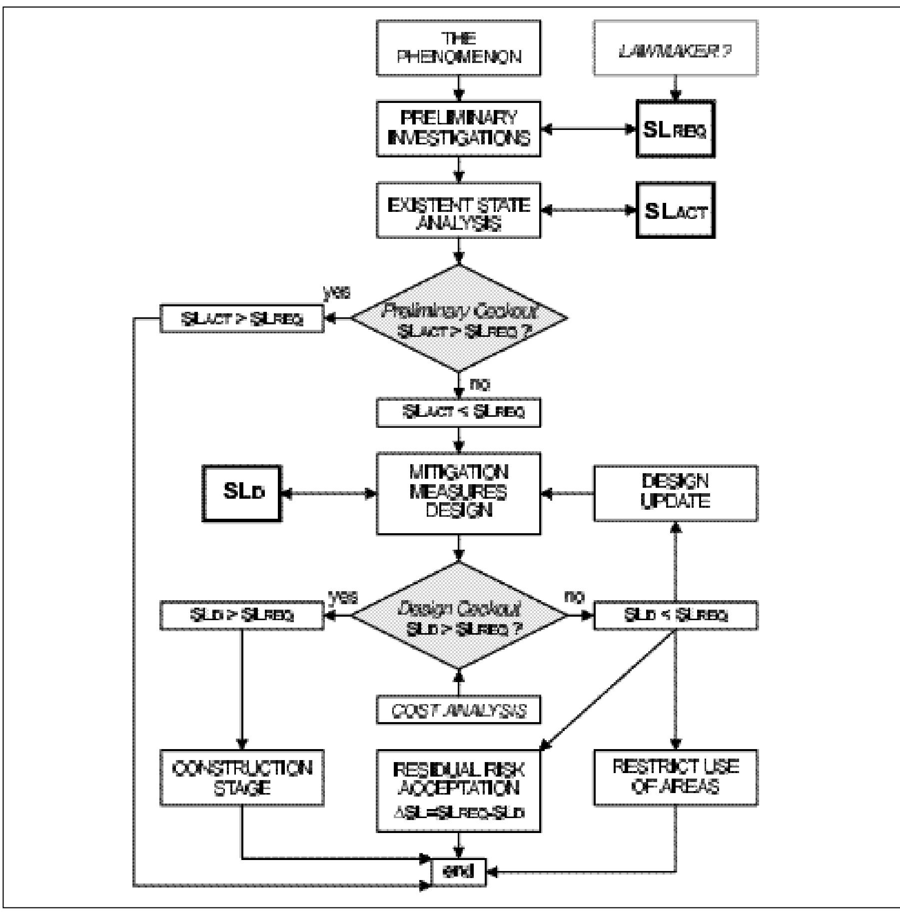

Figure 2. RDBD flowchart, release 1.0.

from economical and land-planning considerations related to infrastructure's development and/or area's utilization. It is well evident that, by means of legislation and administration programs, SL_{REQ} could be integrated in community plans of areas exposed to natural hazards and potential damage. The parameters' assessment could be carried out through risk evaluation techniques (Fell 1994, Einstein 1988, Hudson 1992); however, the value must be defined before any defensive system design is started.

The second probabilistic parameter to define is the *Actual Safety Level* SL_{ACT}, that is the slope intrinsic capacity to stop the block motion, alone (presence of natural dikes or highly forest-areas along the slope) or in combination with pre-existent defensive barriers. When both SL_{REQ} and SL_{ACT} are known, the *Preliminary Checkout* can be performed This step consists in a simple comparison between the above parameters. If the *Required Safety Level* is lower than the *Actual Safety Level*, no defensive works are required. On the contrary, new rockfall barriers must be designed.

In practice, these new defenses "will increase" the *Actual Safety Level until* the reaching of a new probabilistic parameter, the *Design Safety Level* SL_D, which represents the total interception probability of an "ideal" defensive system formed by natural dikes, forest-areas, new and pre-existent rockfall barriers. It is quite clear that the design of a new defensive system must proceed step by step to avoid any superfluous defenses or dangerous underassessment. For this reason, every design step must be checked by the *Design Checkout*, where a comparison between SL_{REQ} and SL_D has been made. As a result, if SL_D is greater than SL_{REQ}, design procedure ends. On the contrary, it is necessary to accept a *Residual Risk Condition*, triggered by the parameter $\Delta SL=SL_{REQ}-SL_D$, or, in the worst case scenario, to relocate infrastructures or forbid human activity.

Preliminary investigations: SL_{REQ} definition. The first historical notices regarding mass movement processes in the study area date back to the 1976 Friuli Earthquake. No rockfall accidents have been reported since that data. In particular, the strong shocks of May 6, 1976, and September 11, 1976, triggered rockfalls in the whole mountainous area of Tagliamento Basin, producing the mobilization of numerous blocks and fragments in Cavazzo Lake Area (Sgobino 1982). In situ investigations carried out in study area allowed to localize, in a topographical plan taken from a Digital Terrain Model, all blocks previously fallen down (Figure 3), and also to observe that new potential block paths could have been involved:

- a 150 m long National Road section (NR512), usually with light traffic;
- a pub and a dancing club sometimes rather crowded (probably 500-1000 people during the weekends);
- a 2000 m^2 car park connected to

the dancing area, sometimes attended by lake's tourists.

In the absence of an adequate technical legislation or specific rules in community plans, the Required Safety Level's choice must be made by the designer (a geotechnical or geomechanical engineer). In this particular instance, taking into account the zone's seismicity and the human presence, a value of $SL_{REQ} = 0.980$ has been directly assigned and considered adequate. No risk evaluation techniques have been used for this purpose.

Preliminary checkout: definition and use of SL_{ACT}. An assessment of SL_{ACT} is necessary to define the actual slope ability to stop the block's motion. Moreover, its definition permits to value the need and importance of possible defensive protection works. An analytical assessment of SL_{ACT} starts with geological, geomorphological and topographical investigations, which supply the different soil types present on the slope and relative geomechanical parameters. They also provide the volumetric probability range of "design" blocks that could fall and bounce down (representative block mass), and probability distribution of elastic restitution coefficient of slope. The research area consists in a sub-vertical rocky cliff 60 m high and 150m wide, with a dolomitic limestone mass and a scree slope at the base characterized by an overall inclination angle of 35°÷40° (medium angular debris, dry and loose). Several rocky outcrops exist at the apex of the scree slope, and the surface is almost completely covered by a 0.1÷0.5m deep soil layer, with shrubs and trees.

Before assessing SL_{ACT}, a "Shadow Angle" qualitative analysis based only on topographical quantities was carried out using the method suggested by Onofri and Candian (1979). Analyzing 98 rockfalls triggered by the 1976 Friuli Earthquake, these authors have found that the "Shadow Angle" between the highest point of rockfall source scar and the stopping point of longest run-out boulder for any given rockfall, is located within the range 28.34°-40.73°. In this case, a value of 39° was found (referred to the axis of National Road section) confirming an effective risk condition of the activities located at the toe of the talus.

On the basis of the historical research and following field evidence it has been possible to assign a mean value of $0.5m^3$ to the representative block mass, with a volumetric class of $0.2÷2m^3$. Besides, because it has a finite range of variability, this quantity has been treated as a beta-distributed random variable, with the following evaluations of PDF (probability density function):

$$\begin{cases} f_X(x) = \dfrac{1}{\beta(q,r)} \cdot \dfrac{(x-a)^{q-1} \cdot (b-x)^{r-1}}{(b-a)^{q+r-1}} & a \le x \le b \\ \beta(q,r) = \displaystyle\int_0^1 x^{q-1} \cdot (1-x)^{r-1} dx \end{cases}$$

and parameter's values *q=1* and *r=5*.

To define the SL_{ACT} value it is necessary to develop a large number of rockfall simulations ($10^4÷10^5$) to generate sample spaces regarding kinematic and energetic parameters triggering block's motion. For this reason, a computer rockfall analysis using a software code that implements a two-dimensional topographical profile model and block's motion through kinematic point laws, has been carried out. The software considers kinematic and energetic parameters as random variables characterized by rectangular, normal, lognormal, gamma and beta probabilistic distributions. Generation of these variables is obtained by means of the *Montecarlo Method*, also utilizing the *Central Limit Theorem*, the *Inversion Method*, the *rejection algorithms* and the statistical properties of any function. In practice, beta distribution appears to be the most interesting, because it can assume various forms and it is particularly appropriate for random variables which have a finite range. This is quite important in Geotechnical and Geomechanical Engineering, where analysis are often concerned with random variables whose values are bounded between finite limits.

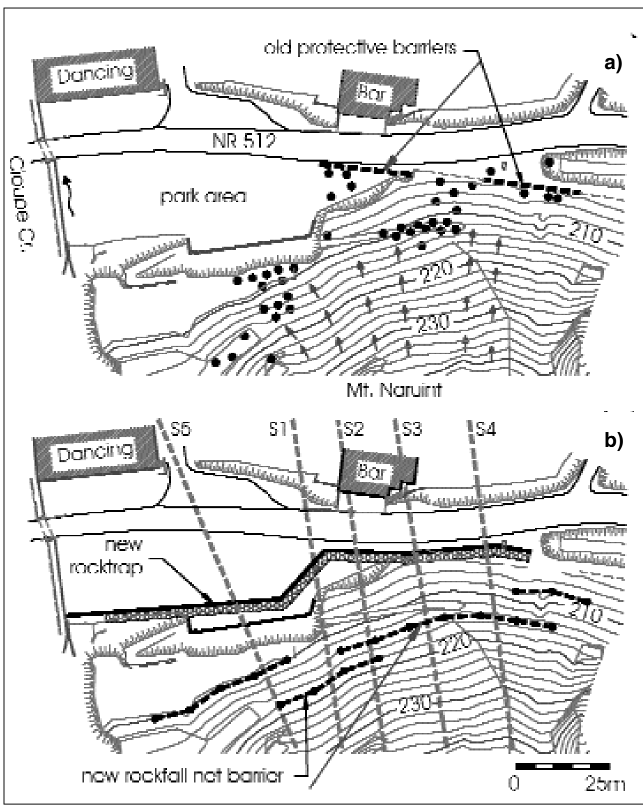

Figure 3. a) Localization of previously fallen down blocks. b) Newly adopted control measures.

The model's calibration of elastic restitution coefficients "e" has been carried out studying the run-out distance (the so called "Rockfall Shadow") of all gathered blocks that had previously fallen down. A satisfactory slope's representation has been obtained through five two-dimensional topographical profiles (S1÷S5) extracted from Digital Terrain Model with reference to the most representative and dangerous potential rockfall paths (Figure 3).

A good agreement with field data has been found using a beta distribution characterized by the following parameter values:

$$\begin{cases} q = 3.8 & r = 2.5 \\ 0 \le e \le 1 & \bar{e} = 0.6 \end{cases}$$

The probabilistic simulations have exhibited exit rebound angles (referred to the slope) within the range 4.5°÷22.5° (in the absence of a rolling phase, this confirms the effective attitude of blocks to generate paths with taut rebound trajectories), and, above all, a minimum SL_{ACT} value of $SL_{ACT} = 0.876$ that implies the following *Preliminary Checkout*:

$$SL_{ACT} = 0.876 < SL_{REQ} = 0.980$$

The latter equation clearly shows the need for defensive barriers, as reported above.

Defensive works choice and effectiveness of defensive works: SLD definition and design checkout. Mitigation works against rockfalls can be classified into two different categories: the "Active Mitigation Systems", preventing detachments of rock blocks from scars (such as contact rock nets, foot protections, ties by rock bolts or wire ropes), and the "Passive Mitigation Systems", intercepting and stopping blocks moving along slopes. The latter can be shelters for falling rock blocks, net fences, and the so-called "rocktraps" (a defensive system generally formed by a back trench and a front dyke). In this particular case the choice is for the Passive Systems.

First of all, according to probabilistic computer simulations developed in the absence of defensive works, the design of a flexible net fence located approximately close to minimum points of envelope's flight height and envelope's block velocity (Figure 4) has been carried out.

The barrier – designed, tested and guaranteed for a 1100 kJ impact energy (in the follow "T.I.E.") by means of adequate crash test – is provided with submarine net panels and friction brakes. The full height of fence is 4m: assuming an 1m high upper clearance and taking into account a setup almost orthogonal to the slope, an effective interception height of 3m has been assigned. The reliability of the designed fence has been developed by means of a simplified Fault Tree Diagram (FTD) (Ang et al. 1984, Paronuzzi et al. 1995). Calling E=fence ineffectiveness (top event), E1= flying over fence, E2=fence collapse, and considering E1, E2 as mutually exclusive, we have:

$$E1 \cap E2 = \emptyset$$

and the probability of top event may be written as follows:

$$P(E) = P(E1) + P(E2)$$

Finally, the fence reliability is:

$$p_{fence} = 1 - P(E) = 1 - P(E1) - P(E2)$$

Note that the use of certified barriers allows to avoid further decompositions of E2, considering basic events such as post impact or net breaking. P(E1) and P(E2) have been assessed on each profile through the analysis of probabilistic simulations, comparing trajectory's height and kinetic energy at barrier's location point with effective interception height and T.I.E. respectively. Results are shown in Table 1 and the consequent inequality:

$$SL_D' = p_{fence} < SL_{REQ} = 0.98$$

representing the *first Design Check-out* on profiles S1÷S5, shows the need to improve the defensive system. For this reason, the mentioned net fence has been supported with a rocktrap located at the limit of the park area and parallel to the National Road. The rocktrap is formed by a traditional stony faced retaining wall, 250cm high, with a shock absorber gabion layer at the back (Figure 5). No artificial back trenches have been made in this case; in addition, due to the landscape it was not possible to

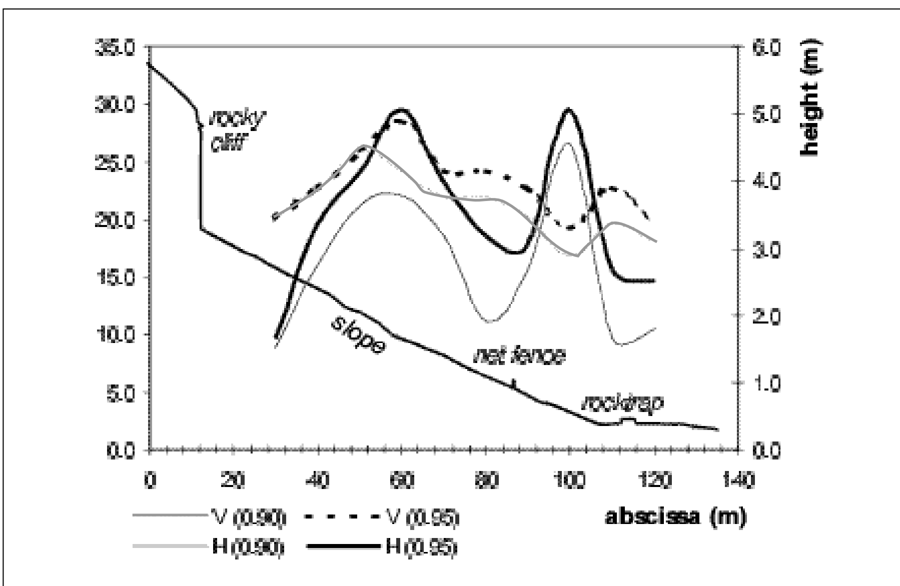

Figure 4. Envelopes of probabilistic parameters (flight height and block velocity) along the slope profile (percentiles 90-95).

exceed the above-mentioned structural height.

The quantification of absorber layer's width was developed by means of Kar's formula (Kar 1978, Paronuzzi 1989):

$$\begin{cases} G_{\left(\frac{x}{d}\right)} = \frac{\alpha}{\sqrt{Y}} \cdot N \cdot \left(\frac{E}{E_s}\right)^{1.25} \cdot \frac{W}{(d)^{2.38}} \cdot \left(\frac{V}{1000}\right)^{1.25} \\ G_{\left(\frac{x}{d}\right)} = \left(\frac{x}{2 \cdot d}\right)^2 \quad \text{if} \quad \frac{x}{d} \leq 2 \\ G_{\left(\frac{x}{d}\right)} = \left(\frac{x}{d} - 1\right) \quad \text{if} \quad \frac{x}{d} \geq 2 \end{cases}$$

in which E, E_s=modulus of elasticity of impactor and steel, respectively, W=impactor weight, N=impactor shape factor, d=outside diameter of impactor or inscribed circle, G=penetration parameter, x=depth of penetration, Y=unconfined static compressive strength of layer.

In the previous equation, an impact velocity at rocktrap's location falling in the range:

$$v_{impact} = 20 \div 25\,m/s$$

has been assessed, according to the results of probabilistic simulations taking into account the net fence installation. Since an average depth of penetration X_{impact}=50cm has been obtained by means of previous equations, a minimum gabion width X_{gabion}=100cm has been considered adequate. The reliability of the integrated defensive system has been as-

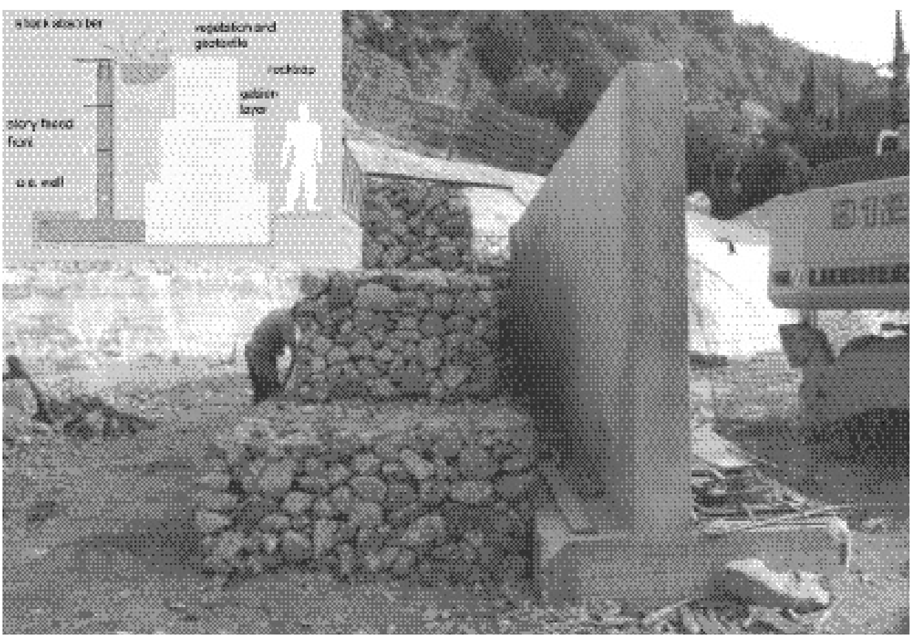

Figure 5. An intermediate stage of rocktrap construction.

Table 1. Fence reliability.

	topographical profiles				
	S1	S2	S3	S4	S5
P(E1)	0.03	0.045	0.002	0.09	0.115
P(E2)	0.00	0.01	0.01	0.01	0.00
P(E)	0.03	0.055	0.012	0.10	0.115
p_{fence}	**0.97**	**0.945**	**0.988**	**0.90**	**0.885**

sessed with reference only to the flying-over of both defensive elements (flexible net fence and rocktrap), according to the following assumption. It seems highly possible that the blocks' motion caused by net fence's structural collapse could end immediately along the barrier's down slope or at the reaching of the rocktrap. These energetic values – referred to the net fence nearby and obtained through probabilistic simulations – do not significantly exceed T.I.E. Furthermore, the higher energetic values have a low occurrence probability.

Then, considering E as defensive flying-over system, occurrence probability values P(E) have been obtained on every slope profile by means of probabilistic simulation and taking into account a 1m. wide upper clearance. See results in Table 2.

Based on the resulting data, the following *second Design Checkout*:

$$SL_D\text{''}=p_{system}>SL_{REQ}=0.98,$$

is satisfied on every S1÷S5 profile, and this enables the conclusion of the design procedure (Figure 6).

For comparison, Table 3 shows over-flying probability values obtained with the rocktrap presence only. One can underline that the above-

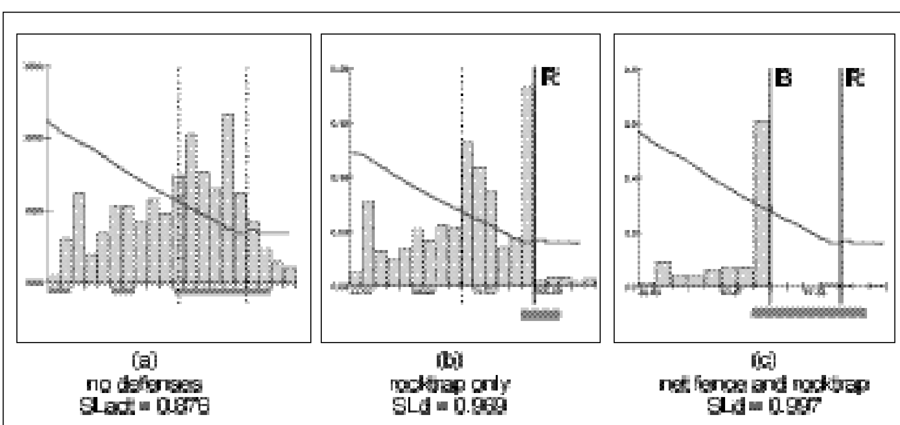

Figure 6. Distribution of endpoints at X locations along the slope (B=net fence, R=rocktrap).

Table 2. System reliability.

	topographical profiles				
	S1	S2	S3	S4	S5
P(E)	0.003	0.002	0.006	0.006	0.007
p_{system}	**0.997**	**0.998**	**0.994**	**0.994**	**0.993**

Table 3. Rocktrap reliability.

	topographical profiles			
	S1	S2	S3	S5
P(E)	0.031	0.023	0.099	0.100
$p^{rocktrap}$	**0.969**	**0.977**	**0.901**	**0.900**

mentioned values do not satisfy the design procedure. This implies the need to develop a multiple defensive system design since it is not possible to increase the structural rocktrap height.

Discussion. The RDBD procedure involves various technical fields and different tools in order to develop passive mitigation systems against rockfalls. This paper shows how a probabilistic approach allows an organized design through tested steps. At present, there are still important and useful elements of this procedure which need to be further explored. Among the future fundamental questions, there is the need to assign the rockfall occurrence probability beforehand. In this particular case, a certain rockfall occurrence has been assumed to be inevitable with SL_{ACT} under the estimated consequences.

Furthermore, the complex defensive system reliability evaluation, such as multiple net fences or mixed net and rocktraps systems, often implies the development of extremely branched Fault Tree Diagrams. In this case, dependent basic events can occur, and the occurrence probability could be quite complex, involving conditional probability and statistical dependence. Finally, within the above indicated limits, the developed procedure can be considered a starting point for a new approach of rockfall defense design which, according to the current phenomenon, must necessarily imply probabilistic techniques.

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