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Rockfall hazard mitigation on infrastructures in volcanic slopes using computer-modelled ditches

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ABSTRACT

Rockfalls on transport infrastructures are a serious hazard to users and many resources are invested in rock slope maintenance, stabilization, and protective measures. In volcanic territories, the risk of rock instabilities and rockfalls is very high due to the rugged natural slopes and origin of rock masses. With the aim of determining the influence of the geometric and material-related properties affecting rockfall motion and the effectiveness of catchment area design criteria, this study applies a computer simulation model considering 150 different slope configurations and ditch geometries, 4 types of materials and 9 size and shape combinations of falling rocks. A statistical analysis of the simulated rock stop-distances was performed. Results show that density, hardness, roundness and size are material properties directly correlated with the rockfall stop-distance. However, block accumulation distribution differs with the rock hardness. Furthermore, practical application design charts are proposed for infrastructure planning and design tasks. These offer the ditch dimensions depending on the relation between the optimal stop-distance and the cumulative percentage retained along the trajectory, complying with specific retention requirements, and optimize the dimensions of previous studies. A triangular ditch of foreslope steepness 14º offered better retention capacity and road safety than a deep flat-bottom ditch. These rockfall protection areas constitute non-structural defence measures of reduced environmental impact and cost in volcanic territories.

Keywords*:* Road slope; Rockfall catchment area; Ditch; Rockfall passive protection; Rockfall stop-distance; Volcanic terrain

Highlights:

- Block density, hardness, stiffness, roundness and size show a direct correlation with the rockfall stop-distance.

- Triangular ditches with steeper foreslope gradient present higher retention capacity and better road safety than deep flat-bottom ditches.
- Block accumulation shows bimodal distribution for hard rock slopes, being unimodal for soft lithotypes.
- The ditch design charts proposed optimize the dimensions of rockfall catchment areas of previous studies.
- These defence ditches offer economic and environmental advantages compared to other structural solutions.

1. Introduction

In volcanic territories, such as many island regions with this geological origin, the risk of rock instability and rockfalls on transport infrastructures is prominent because of both topographical and lithological factors. The rugged natural relief makes it necessary to design roads and railways with limited width and steep adjacent slopes. The lithological characteristics, origin of rock masses, and even seismicity result in rock slopes with abundant potentially unstable blocks.

Rockfall protection does not have a single, clear solution. There is a wide range of possible situations that require specific treatment and engineering [1]. The use of catchment areas to reduce the hazardous consequences of rockfalls on transport infrastructures is a simple, economic and effective measure [2-5]. It also means low environmental impact and easy maintenance. In fact, this is a competitive solution compared to stabilization structures (mesh, bolts, anchors) or defence constructions (dynamic rockfall barriers, retaining walls, fences, tunnels), that usually require important financial investment [4]. Catchment areas are therefore an ideal method for protection of infrastructures in developing countries or with limited economic resources.

Ritchie (1963) [2] identified the characteristics of rockfall motion and proposed a graphic design chart and tables to determine the minimum depth and width of catchment ditches according to slope height and gradient, establishing the impact distance of a rockfall as a function of the slope height and steepness. This author proposed a deep flat-bottomed ditch (up to 2 m) of variable width, connected to the roadway by a constant foreslope (1.25H/1V). This graphic chart and its version modified by the FHWA [6] represented a significant step forward in highway and railway protection design (Fig. 1). However, Ritchie´s model is now seen to have some limitations: a) it does not provide a cost criterion allowing for choice of the most suitable capacity of block retention for each slope section; b) it offers results for only one geometry (trapezoidal ditch); and c) this deep and steeply-sloped ditch design makes it difficult for vehicles to return to the roadway safely as well as difficult maintenance of roadway margins.

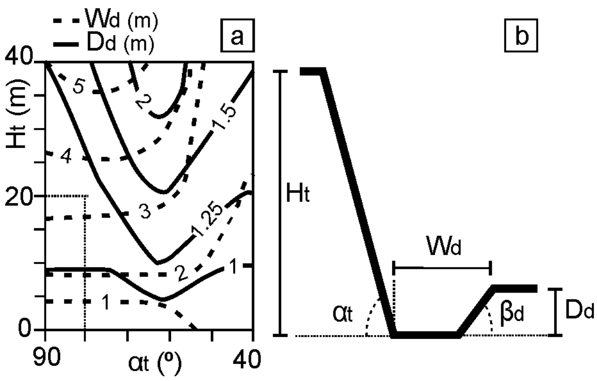

Fig. 1. Rockfall catchment ditch design chart inspired upon Ritchie's work (1963): a) Graphical chart to obtain ditch dimensions for a certain slope topographical configuration. [E.g. for a slope 20 m high and at 80º, the proposed ditch has 3.3 m wide and 1.2 m deep]; b) Cross section of the slope-ditch configuration: (H_t) Slope height, (α_t) Slope gradient, (W_d) ditch width, (D_d) Ditch depth, (β_d) ditch gradient.

After Ritchie´s research, some authors have evaluated the mechanics of rockfalls [7-16]. The Oregon Department of Transportation (ODOT) carried out on site experimental work between 1992 and 1994, gathering data from three types of catchment areas with different gradients (1H/0V or flat, 6H/1V and 4H/1V). To validate this work, blocks from different slope heights (40, 60 and 80 feet) over a constant gradient (0.25H/1V) were rolled out [17]. The results provided an estimation of rockfall frequency, quantified the probability of blocks reaching the road, and verified the retention capacity of catchment areas. In 2001, the ODOT and the FHWA evaluated other configurations of the slope-ditch system. They rolled 11,250 blocks of different sizes over different slope gradients (0.25H/1V; 0.5H/1V; 0.75H/1V and 1H/1V) and from differing heights (40, 60 and 80 feet). In this occasion, three kinds of triangular ditches were evaluated (1H/0V; 6H/1V and 4H/1V). The results allowed new design charts to be drawn up [3].

A more economical and practical approach using numerous numerical simulation tools have been developed based on the rockfall motion equations and interactions between the blocks and the slope [18-23]. Pantelidis (2010) [4] used "RocFall" computer program (Rocscience, 2002) to develop adapted graphic charts for catchment areas based on the Ritchie ditch: deep flat bottom, covered by a gravel layer and with vegetation coverage at the edges. His research was based on the results of 100 rocks falling over hard rock slope with a catchment area at the base. Moreover, Ref. [24] considered the use of additional structures (fences and concrete walls).

Consequently, the catchment areas have not followed standardized design criteria. Those designed by using empirical design charts may not be optimized and some might present unsafe conditions for road traffic. Moreover, there are no standard specifications for computer-designed catchment areas at present. As a result, there are many types of ditches —some oversized and others with low efficiency— which has led to higher costs and higher environmental impact. Thus, new design criteria that are more rational and quantitative must be found to solve this problem.

This study offers a useful tool to optimize the slope-bench-ditch system design, permitting easy evaluation of its retention capacity at the planning stage or even when built, and justification of any possible improvements. The criteria applied are quantitative and are based on numerical models. Five different geometric factors were assessed to determine the stop-distance of rockfalls: shape (F_b) and size (S_b) of the blocks, slope height (H_t), slope gradient (α_t), and foreslope steepness of the catchment ditch (α_d) [Fig. 2]. Both gradients (slope and ditch) are also expressed as a relation between the triangle sides (H/V). Moreover, other material-related factors such as density and hardness were also considered. This produces a wide combination of possible values in these inputs, generating multiple arrangements and output data.

The results obtained allow the estimation of the frequency of rock accumulation at different distances, quantify the probability of these blocks reaching the roadway and verify the retention capacity of the proposed catchment areas. These may be designed using the practical graphic charts produced in this study. These rockfall protection ditches constitute defence measures with a reduced environmental impact and much lower cost compared to other structural solutions. Furthermore, the interest and opportunity of this topic acquires special relevance in order to save costs at the planning stage of construction projects and also in the maintenance of transport infrastructures.

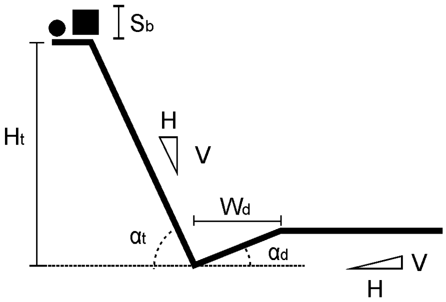

Fig. 2. Schematic cross section with the geometric parameters considered for modelling: (S_b) block size, (H_t) slope height, (α_t) slope gradient, (W_d) ditch width, (α_d) ditch foreslope steepness. Different block shapes with diverse roundness coefficient are also considered.

2. Method

When designing passive protection systems to mitigate rockfall hazards, standard practice is first to simulate the block trajectory and then determine the optimal location and geometry for the chosen solution according to the circumstances of the infrastructure to be protected. The “Colorado Rockfall Simulation Program” (CRSP) was used to perform the simulation, as employed in previous studies [20,25]. This computer program offers values for 4 rockfall parameters: velocity (V_i), kinetic energy (E_k) and block rebound height (H_r), according to the established analysis partition, and the run-out distance referred to the slope summit. These values allow to estimate the rockfall reach and evaluate the design of block retention structures.

In our analysis 150 slope-bench-ditch topographic arrangements were considered, combining different slope heights (H_t), slope gradients (α_t), and ditches of different foreslope steepness (α_d) (Fig. 3). Furthermore, two different extremal lithologies for the terrain (Hard Rock, HR; and Soft Rock, SR) were considered (see Table 2), so as any other lithology could have an intermediate performance. The geomechanical properties of the terrain (density [D_b], hardness and stiffness [I_h], roughness [R]) and the block properties (shape or roundness [F_b], size [S_b]) were taken into account as determined following CRSP criteria [26]. The combination of all these variables defined 1,125 cases, each with 30 rockfall events analysed, giving a total of 33,750 results obtained.

Tables 1 and 2 summarize the different values of the parameters used for modelling: a) 5 slope heights (H_t); b) 5 slope gradients (α_t); c) 2 slope configurations, including the presence of a bench (1 m wide) at 12 m of the slope height; d) 3 ditch foreslope steepness (α_d); e) 4 materials (hard and soft rock for the natural slope, concrete for the ditch, and asphalt for the road pavement) with properties (density, stiffness and roughness) established according to references mentioned on Table 2; f) 9 combinations of possible blocks for hard rock and 6 for soft rock, depending on their shape (cubic, cylindrical, spherical) and size (0.3, 0.6 and 0.9 m; these correspond to frequent dimensions of rock blocks due to thermal retraction cracks generated during the cooling of volcanic geomaterials); g) the launch point of the blocks was random, along the entire slope, assuming that falling blocks start at rest. This is the most common situation on homogeneous and anisotropic slopes (a single rock type and the same weathering grade). The variation range of the parameters used for modelling covers the usual values in engineering projects constructed on rugged rock reliefs such as those in volcanic island territories.

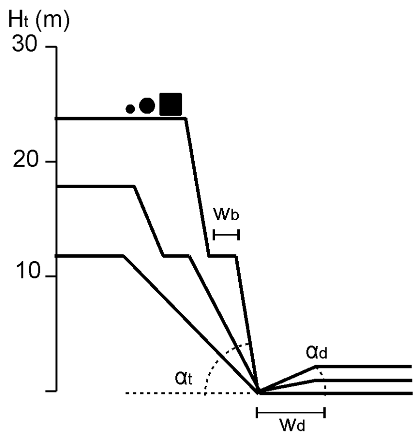

Fig. 3. Modelled topographical cross sections with different configurations of the slope-bench-ditch-roadway system and the geometric factors considered for ditch design: block size, block shape, slope height (H_t) [some including a bench (W_b)], slope gradient (α_t), ditch width (W_d), and ditch foreslope steepness (α_d). The variation range of these parameters is detailed in Table 1.

Table 1

Geometric parameters of the slope-ditch system and blocks used in rockfall modelling.

Slope			**Ditch**		**Block**	
H_t (m)	**$(H/V)_t$ (m/m)**	**α_t (º)**	**$(H/V)_d$ (m/m)**	**α_d (º)**	**F_b (-)**	**S_b (m)**
12	1/1	45	1/0	0	cube	0.3
15	1/2	63	6/1	9.4	cylinder	0.6
18(*)	1/3	71	4/1	14	sphere	0.9
21(*)	1/4	75				
24(*)	1/6	80				

(H_t) Slope height; (α_t) Slope gradient; (α_d) Ditch foreslope steepness (both expressed as the relation between horizontal [H] and vertical [V] distances); (F_b) Block shape; (S_b) Block size; (*) Slope with a 1 m wide bench located at a height of 12 m

Analysis required the following inputs: a) coordinates of the slope section; b) roughness and hardness of the selected materials; c) launch location, number, shape and size of the blocks; d) specific weight of the materials; e) analysis partition to obtain the results of the parameters analysed (velocity, kinetic energy, block rebound height and roll-out stop-distance [X_{stop}]). In this study, the analysis partition was located at the edge of the roadway, so as to minimize the number of blocks reaching the road pavement.

Table 2

Geomechanical parameters of the different materials used in rockfall modelling.

Parameter	**Value**
Lithology (L)	Hard Rock (HR) Soft Rock (SR) Concrete (C) Asphalt (A)
Roughness (R); [m]	0.3-0.6 (HR) 0.3-0.6 (SR) 0.03-0.3 (C) 0.03-0.3 (A)
Hardness index (I_h); [-]	0.8-1 (HR) 0.3-0.5 (SR) 1 (C) 0.9 (A)
Bulk density (D_b); [kN/m^3]	23-24 (HR) 11 (SR) 24 (C) 23.5 (A)

(L) Lithology: HR (massive basalt) and SR (pumice) [27-29]; (R) Coefficient relating the slope surface geometry with the block radius [26]; (I_h) Hardness index [related to the stiffness, to the tangential and normal restitution coefficients and to damping coefficients] [26]; (D_b) Bulk density [27-29]

The software uses an algorithm with the general motion equations to simulate the block speed and the contact forces between the rock and the slope. Six parameters were used to simulate block impact: slope geometry, hardness and roughness of the terrain, density, shape and size of the block. Roughness is used to model the slope surface and is defined by a single value. Hardness is related to 2 coefficients [26]: the restitution coefficient (indicative of the impact elasticity) and the damping coefficient (indicative of the block tangential resistance). The computer simulation offers 5 outputs: velocity, kinetic energy, block rebound height and the roll-out stop-distance (X_{stop}) referred to the analysis partition.

Results were classified depending on the lithotype, slope height, slope gradient, and type of catchment area. Each case was given an identification code according to its characteristics. In each case, the topographical configuration was represented by 2D slope cross sections, where the coordinate origin was located at the top of the slope. Stop distance (X_{stop}) is shown on the X axis, and slope height (H_t) on the Y axis. A 2-Dimensional approach is justified because this analysis focuses on constructed or excavated slopes, not on natural slopes and thus, these slopes are usually designed with the same gradient along certain distance, generating surfaces that can be assumed to be ideally plane.

In order to represent all the results in the same range of distances and to compare them, the origin of coordinates had to be displaced to the bottom of the slope. Therefore, the roll-out stop distances had to be modified by deducting the horizontal projection of the slope. These new distances were named as corrected distances. Based on these new values, statistical parameters were calculated to characterize and compare the 1,125 design cases (average, standard deviation, asymmetry, Kurtosis index).

At the same time, a change of variable was applied to the X-axis to represent the results as a Fi-normal distribution function and be able to establish statistic relations. The origin of the X-axis coincides with the base of the slope. Data distribution was restricted to the -∞ to +13 m range, so as to represent all the configurations. This range is able to include a maximum ditch width (W_d) of 5 m, a roadway width of 8 m and any possible slope geometry (H_t; α_t). These adjustments allowed to present the results of the 1,125 cases analysed in the same range of normalized distances (X_{stop}*) and to establish comparisons between their basic aforementioned statistical parameters. All the roll-out stop distances data (X_{stop}*) are available in a supplementary file (see Table 7 in Electronic Supplementary Material).

The range of distance values (-∞ to +13 m) was divided into unit sections (1 m). For each section, the absolute frequencies of retained blocks were calculated in percentages (%Rt) expressed in relation to the sum of all the events simulated for each case (n = 30). The cumulative percentage (%Cum) was then calculated for each unit section (Fig. 4).

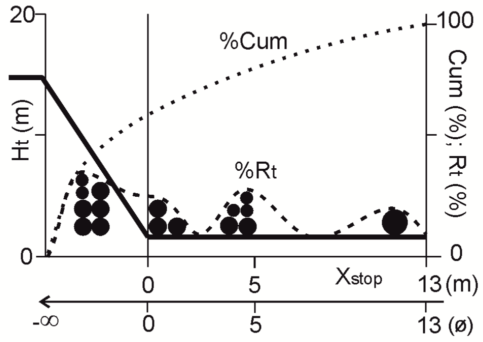

Fig. 4. Schematic representation of (%Rt) and (%Cum) distributions versus the stop-distance (X_{stop}) based on Fi-normal distribution (ϕ). (H_t) Slope height; (%Rt) Percentage of retained blocks; (%Cum) Cumulative percentage of block retention.

The optimal stop-distance (X_{opt}) was determined based on the cumulative percentage (%Cum), and represents the distance corresponding to 95% of block retention. This estimation represents a reliability threshold of 95% in the ditch design, which is a frequent safety margin in civil engineering design. X_{opt} was calculated by interpolation of the closest values to 95%. Each geometric configuration and rockfall event has its own optimal stop-distance (Fig. 5).

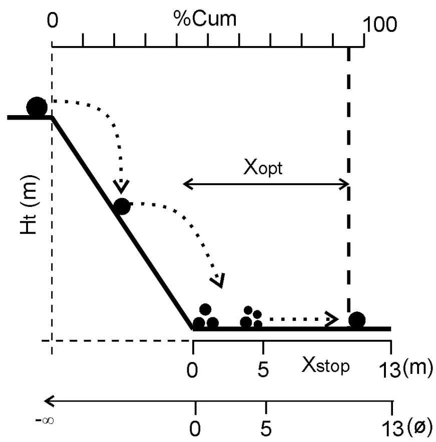

Fig. 5. Graphical scheme of the cumulative percentage of retained blocks (%Cum) with regard to the block stop-distance (X_{stop}). Example of a topographical cross section where the optimal stop distance (X_{opt}) is calculated for a 95% of block retention.

A set of graphs were drawn up using all the optimal stop-distance values (X_{opt}) in order to determine the influence of 5 factors on the block stop-distances. These factors were: slope height (H_t), slope gradient (α_t), ditch steepness (α_d); shape (F_b) and block size (S_b). For each graph, the statistical distribution of values and fitting functions of 3 characteristic percentiles (P_{95}, P_{50}, and P_5) were analysed (Fig. 6).

Finally, graphical relations were determined between any cumulative percentage of rocks (%Cum) and the normalized stop-distance (X_{stop}*). For each slope configuration (H_t, α_t), the (%Cum-X_{stop}*) functions of the 3 types of ditches (flat [1H/0V], 10° [6H/1V] and 14° [4H/1V]) were plotted (see Fig. 13 in Electronic Supplementary Material). These ditch gradients are compatible with road traffic safety. The design charts were only plotted for cubic blocks, because cubes are the most frequent block geometry in the lithotypes evaluated, both representative of volcanic hard rocks and soft rocks. These representative volcanic lithotypes were the massive basalt (HR) and the pumice (SR); this last type is a non-welded phonolitic ignimbrite. The geotechnical properties were obtained from Ref. [27-29]; these laboratory and field studies offer exhaustive data concerning most volcanic rock lithotypes.

3. Results

The results generated have been distributed into three sections: a) Factors affecting the rockfall stop-distance, b) Practical charts to design and optimize the catchment areas, and c) Relations between the optimal ditch width and the topographical parameters.

3.1. Influential factors of the rockfall stop-distance

As detailed below, some observations were made after relating the optimal stop-distance (X_{opt}) with the influential geometric factors: H_t, α_t, α_d, F_b and S_b (Fig. 6). The linear fitting functions define a moderately good fitting, not only for hard rock (HR) but also for soft rock (SR). The parameters of the linear functions are shown in Table 3. However, the trend of the fitting function for percentile P_{95} in HR is usually very different compared to the rest of percentiles evaluated, especially in the representation of H_t (Fig. 6a) and α_t (Fig. 6b). It must be noted that statistical distributions of X_{opt} are always asymmetrical (positive skewness) with an average X_{opt} <5 m.

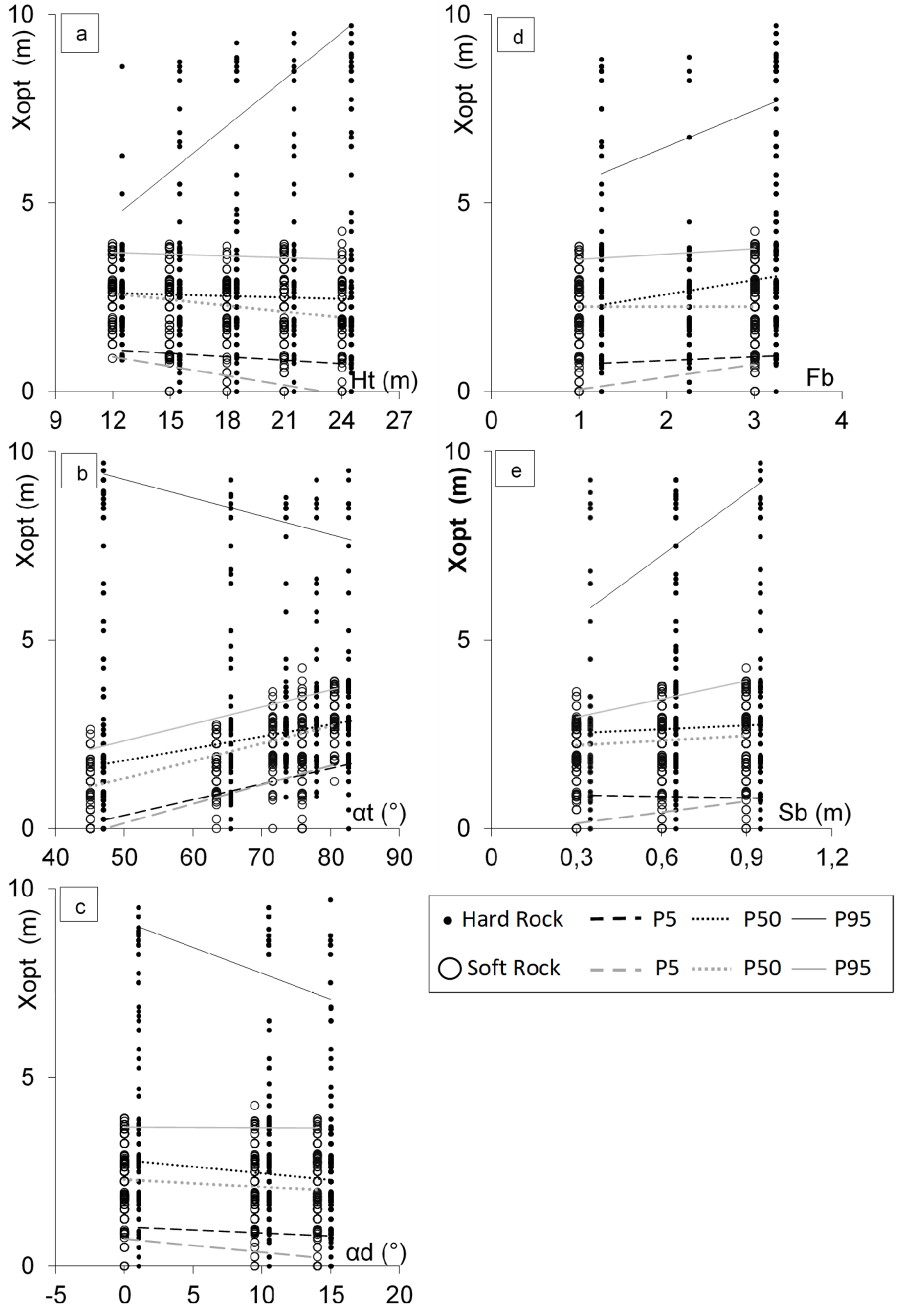

Fig. 6. Distribution of X_{opt} obtained by numerical simulation for the two lithotypes (Hard rock, HR; and Soft rock, SR). Each graph represents the relation between X_{opt} and a different geometric parameter: a) X_{opt} vs. slope height (H_t); b) X_{opt} vs. slope gradient (α_t); c) X_{opt} vs. ditch steepness (α_d); d) X_{opt} vs. block shape (F_b) [roundness code: (1) cube; (2) cylinder; (3) sphere]; e) X_{opt} vs. block size (S_b). The fitting functions for the characteristic percentiles (P_{95}, P_{50}, P_5) are also represented (see Table 3). Note: HR is represented by dots and SR by circles.

Table 3

Linear fitting functions of X_{opt} characteristic percentiles (P_{95}, P_{50}) obtained after simulation. These functions are plotted in Fig. 6.

Functions		**Hard rock (HR)**		**Soft rock (SR)**	
		P_{50}	**P_{95}**	**P_{50}**	**P_{95}**
$X_{opt} = a \cdot H_t + b$	a	-0.0125	0.4103	-0.0533	-0.0154
	b	2.7563	-0.3292	3.2375	3.8707
	χ^2	0.1023	0.8362	0.9018	0.1130
$X_{opt} = a \cdot \alpha_t + b$	a	0.0487	-0.0319	0.0461	0.0448
	b	0.2053	11.694	-0.9700	0.0821
	χ^2	0.7245	0.9262	0.8197	0.7702
$X_{opt} = a \cdot \alpha_d + b$	a	-0.0343	-0.138	-0.0201	-0.0015
	b	2.8026	9.1271	2.2965	3.6846
	χ^2	0.9592	0.6482	0.5583	0.0427
$X_{opt} = a \cdot F_b + b$	a	0.3750	0.9625	$2.0 \cdot 10^{-15}$	0.1429
	b	1.8229	4.5677	2.2500	3.3571
	χ^2	0.5192	0.1134	1.0000	1.0000
$X_{opt} = a \cdot S_b + b$	a	0.3333	5.5417	0.4167	1.5961
	b	2.4333	3.9146	2.0833	2,4743
	χ^2	0.5714	0.7500	0.7500	0.9424

(H_t) Slope height in m; (α_t) Slope gradient in degrees; (α_d) Ditch steepness in degrees; (F_b) Block shape (cube = 1, cylinder = 2, sphere = 3); (S_b) Block size in m; (χ^2) Chi-Square.

X_{opt} increases with increasing values of α_t, F_b and S_b. Thus, these factors have a direct relation with X_{opt} (Fig. 6b, Fig. 6d, Fig. 6e), although the function of percentile P_{95} in the representations of α_t shows a negative trend for the HR lithotype (Fig. 6b). On the contrary, the observed trend of H_t and α_d is negative. This means that these factors have an inverted relation with X_{opt} (Fig. 6a, Fig. 6c); however, it was found that the fitting function of percentile P_{95} for H_t shows a positive trend for the HR lithotype (Fig. 6a).

The X_{opt} distribution for SR is unimodal and is concentrated below the reference value $(W_d)_{max.}$= 5 m accepted in this study. On the contrary, the dispersion of calculated values for X_{opt} in HR shows bimodal distribution. Blocks are concentrated near the base of the slope (1-4 m) and between 7 and 9 m. Both observations allow to define an optimal ditch width (W_d) of 4 m for these materials.

These general trends present some nuances. On one hand, the X_{opt} distribution with regard to H_t has several gaps in HR slopes over 15 m high. These gaps can be observed when $X_{opt} > 5$ m. Nevertheless, there is no clear linear relation concerning the space between gaps and slope height (H_t) (Fig. 6a). On the other hand, it was found that ditch steepness (α_d) is more effective in steeper ditches (≥14º). Only in these cases, there is a significant reduction of rockfall stop-distance (P_{95}) (Fig. 6c). Finally, there is also an important increase (1-2 m) in rockfall stop-distance for percentile P_{95} when the round shape of blocks increases (Fig. 6d).

3.2. Catchment area graphical design charts

A total of 50 ditch design charts were drawn up, based on the relations between the cumulative percentage of rocks (%Cum) and the rockfall stop-distance (X_{stop}*), one per slope configuration (H_t, α_t). All these graphics are included as Electronic Supplementary Material in Fig. 13. In each chart the corresponding functions for ditches with different steepness (flat [1H/0V], 10º [6H/1V] and 14º [4H/1V]) are presented, including a horizontal line to represent the 95% percentile (P_{95}) in order to facilitate interpretation of the optimal ditch width (W_d) capable of retaining the most suitable percentage of blocks (%Cum) for designing tasks.

With these design charts it is possible to determine the suitable dimensions for ditches during the planning stage following these 4 steps (Fig. 7a): 1) define the cross section geometry for the projected slope (H_t, α_t); 2) select the appropriate design chart (%Cum-W_d); 3) assume a certain reliability threshold to obtain the desired percentage of retained blocks (%Cum). Most engineering projects frequently assume a 95% of reliability (%Cum = 95%); 4) intersect the horizontal line with the curves for different ditch steepness (α_d) and select on the X axis the most efficient ditch width (W_d).

Likewise, these charts also make a possible inverse interpretation (Fig. 7b), and thus evaluate the efficiency of an existing ditch (W_d, α_d), for a specific slope configuration (H_t, α_t), in 4 steps: 1) select the appropriate design chart (%Cum-W_d) for the cross section geometry of the existing slope; 2) choose the corresponding function with α_d more similar to the steepness of the existing ditch; 3) intersect the vertical line with the chosen curve and obtain on the Y axis the cumulative percentage of rocks (%Cum) that the existing ditch would be able to retain; 4) evaluate whether the retained blocks percentage (%Cum) is sufficient, or whether the assumed reliability percentage could be an unwanted risk factor.

In both analysis, the chosen option must be corroborated with a comparative cost assessment.

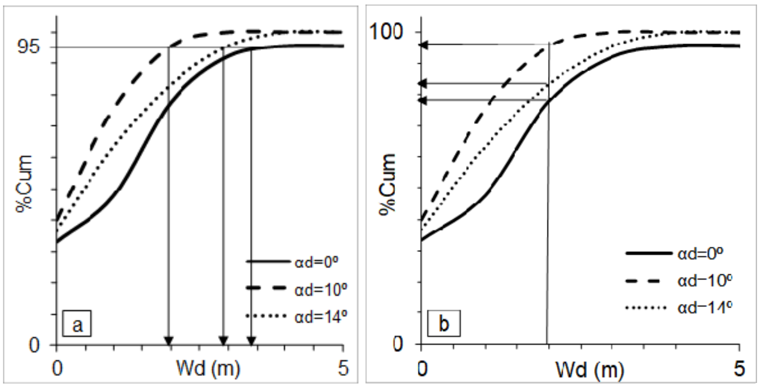

Fig. 7. Examples of graphic design chart interpretation. Here a case is considered with the following parameters: $H_t = 15$; $\alpha_t = 75º$; L = HR; F_b = cube; $S_b = 0.9$ m: a) The %Cum = 95% provides optimal ditch widths [2 m < W_d < 3.5 m] able to retain 95% of potential rockfalls; b) A ditch width W_d = 2 m provides retention percentages between 78-95%, depending on ditch steepness (α_d).

3.3. Relations between the optimal ditch width and the topographical parameters

The role of topography in the numerical modelling of stability of constructions in rock was assessed in previous research [30]. The optimal catchment ditch width (W_d) has certain relations with the geometric factors (H_t, α_t, α_d). Fig. 8 compares the W_d values for some different slope-ditch configurations varying the aforementioned topographical parameters. In this figure the following observations can be drawn:

- An increase in slope height (H_t) may obtain, under certain circumstances, the desired proportion of block retention (%Cum = 95%) with lower values of W_d. Fig. 8a shows the comparison of two extreme situations (different H_t; the same α_t and α_d) that confirms this observation.

- Secondly, an increase in slope gradient (α_t) may imply, under certain configuration of factors, an increase in W_d to achieve a desired percentage of block retention. Fig. 8b compares two extreme cases (the same H_t and α_d; different α_t) that bears out this observation.

- Thirdly, Fig. 8c shows that an increase in ditch steepness (α_d) reduces the W_d required to achieve the expected percentage of block retention (%Cum = 95%).

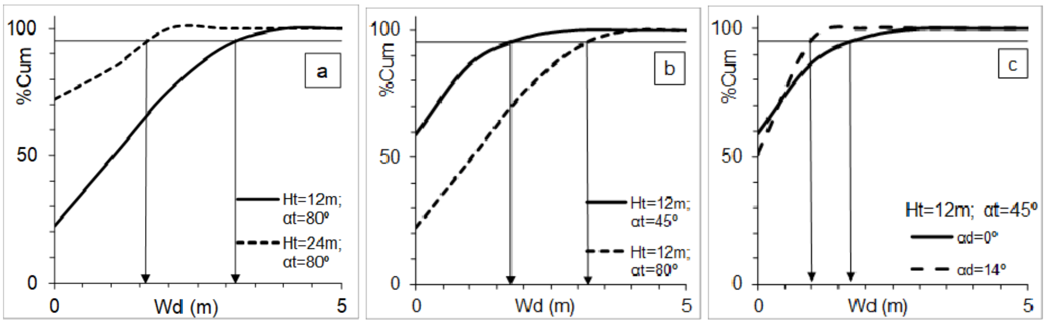

Fig. 8. Specific slope-ditch arrangements to show the influence of topographic and geometric factors on the optimal W_d: a) Different slope height but same slope gradient and ditch steepness; b) Same slope height but different slope gradient and ditch steepness; c) Same slope height and slope gradient but different ditch steepness. (H_t) Slope height; (α_t) Slope gradient; (W_d) Ditch width; (α_d) Ditch steepness; (%Cum) Cumulative percentage of block retention.

Fig. 9 presents four representative situations from the 50 cases analysed. Each case shows the retention capacity of the ditches with different steepness (flat [1H/0V], 10º [6H/1V] and 14º [4H/1V]) and width. (The rest of design charts can be consulted in Fig. 13 as Electronic Supplementary Material).

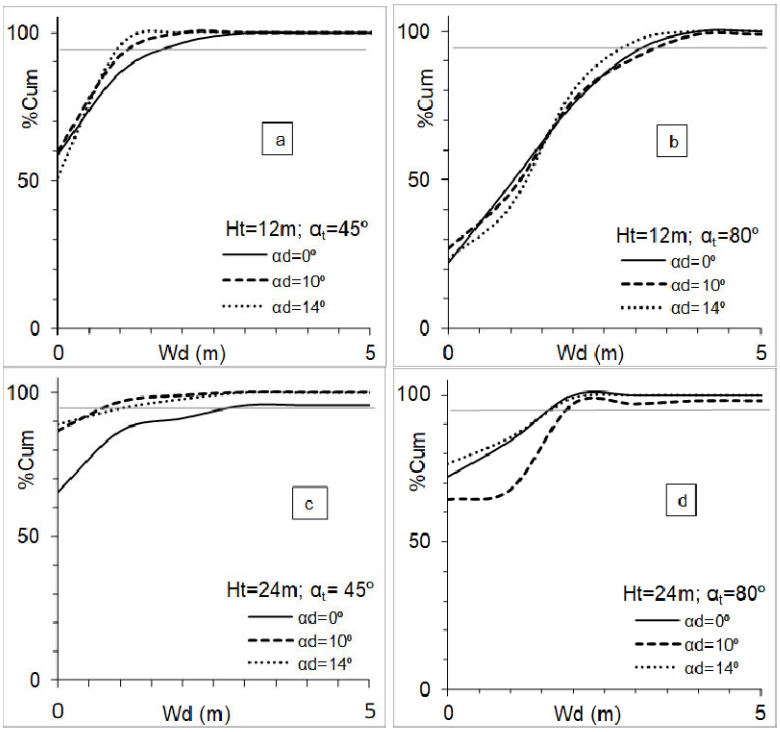

Fig. 9. Design charts for 12 slope-ditch arrangements. Extreme situations of slope height and slope gradient are presented. These charts offer the optimal ditch width (W_d) for a required percentage of block retention: a) Design chart for a 12 m height and 45º slope; b) Design chart for a 12 m height and 80º slope; c) Design chart for a 24 m height and 45º slope; d) Design chart for a 24 m height and 80º slope.

4. Final discussion

4.1. Factors affecting the rockfall stop-distance

In this section the results obtained of rockfall stop-distance corresponding to 95% of block retention (X_{opt}) leading to an optimal catchment ditch width (W_d) are discussed in relation with the different factors affecting them.

Slope height (H_t):

A higher H_t means greater potential energy, thus suggesting in advance a longer stop-distance for 95% of block retention (X_{opt}). However, an increase of H_t also implies a longer trajectory and so energy loss due to roll-out or rebound is higher. This fact can help to improve the retention capacity of the whole slope-ditch system and explains certain results. Furthermore, the inverse correlation between the slope height (H_t) and the optimal catchment ditch width (W_d) under certain configurations of the geometric factors (as shown in Fig. 8a) could also be associated with the fact that the highest slopes analysed in this study ($H_t \geq$ 15 m) include a bench in mid-slope that may serve as an additional catchment area.

Slope gradient (α_t):

Rocks usually roll over moderate gradients (30º-45º) [2]. Friction between block and slope surface reduces the energy, slows the motion and, as a result, reduces the stop-distance (X_{opt}). However, when α_t rises (45º-70º), the bounce probability increases and thus, friction decreases. This situation could be responsible of an increase in X_{opt} and of the direct correlation between the slope gradient (α_t) and W_d observed in that cases (Fig. 8b). On the contrary, on steeper gradients (>70º-80º) blocks usually descend in free fall [8,31], impacting at the slope base and thus can reduce X_{opt}. Therefore, results suggest that X_{opt} is greater for intermediate gradients, as established by other previous studies [32].

Ditch steepness (α_d):

An increase of α_d improves the retention capacity of the whole catchment system (slope-ditch) because the rockfall stop-distance can be reduced due to the effect of foreslopes [3]. Thus, the inverse correlation between the ditch steepness (α_d) and W_d in all situations (Fig. 6c, Fig. 8c) would be related to the rebound direction change determined by such ditch foreslope, because blocks require more energy to keep rolling against the gravity. It can be observed that the influence of the ditch foreslope gradient (α_d) is effective in the steepest ditches (≥14º). Reduction of the optimal stop-distance (P_{95}) is only significant in these cases. In flat ditches (1H/0V) the X_{opt} is almost 1,8 m larger than in steeper ditches (4H/1V) (Fig. 8c).

Block shape and size (F_b, S_b):

The less spherical the block, the larger the contact area between block and surface, meaning that the block has higher friction or resistance to movement [11,12,33]. In addition, more energy is needed to make blocks roll because they have to overcome more friction when rolling [9]. In contrast, the bigger the block, the higher the mass, so its initial potential energy partially counteracts the previously described effects, favouring an increase in X_{opt}.

Bulk density (D_b):

The higher the density of the blocks, the more mass they have, and thus their superior initial energy results in greater distances. In addition, the hardness of the material generally increases and consequently, the kinetic energy loss is reduced at impacts. All these factors contribute to longer stop distances. Moreover, higher density normally means higher block resistance to fragmentation and this implies lower probability of breakage. Accordingly, the potential damage associated with rockfalls may be greater.

Hardness index (I_h):

Hardness index (I_h) depends on the restitution coefficient (K) of the kinetic energy (E_k) when an impact takes place ($0 < K < 1$). K increases according to the material elasticity (ε). When ε increases, the speed loss of the block is reduced ($V_v = V_f - V_i$) at impacts and consequently the energy loss is also reduced. On the contrary, in slopes with low K, impacts are better absorbed and lose more E_k, meaning that stop distances (X_{opt}) are shorter [7,34].

Table 4 summarizes, not in quantitative terms, the relations among every influential factor affecting block stop-distance and the performance variables involved in rock motion.

Table 4

Graphic summary of relations (direct or indirect) among the influential factors of rockfall stop-distance and the different parameters related to rockfall performance (according to Section 4.1).

		Rockfall motion parameters					X_{stop}	
Material factors		**M**	**E**	**ε**	F_s	E_{loss}	P_{50}	P_{95}
Bulk Density	(D_b)	↑	↑	↑	↑	↓	↑	↑
Hardness Index	(I_h)	-	-	↑	↓	↓	↑	↑
Roundness Coefficient	(F_b)	-	-	-	↓	↓	↑	↑
Block Size	(S_b)	↑	↑	-	-	-	↑	↑

		Rockfall motion parameters					X_{stop}	
Slope geometric factors		**M**	**E**	**ε**	F_s	E_a	P_{50}	P_{95}
Slope Height	(H_t)	-	↑	-	↑	↑	↓	↑
Slope Gradient	(α_t)	-	↑	-	↓	↓	↑	↓

		Rockfall motion parameters					X_{stop}	
Ditch geometric factors		**M**	**E**	**ε**	F_s	E_a	P_{50}	P_{95}
Ditch Steepness	(α_d)	-	↓	-	-	-	↓	↓

(M) Mass; (E) Total energy, equal to the sum of kinetic and potential energy; (ε) Elasticity; (Fs) Friction strength; (E_{loss}) Energy loss due to friction and elasticity; (P_{50}) Percentile 50% of stop-distance statistical distribution; (P_{95}) Percentile 95% of stop-distance statistical distribution. (Arrow pointing up means a direct relation between both parameters; if pointing down means an inverse relation).

4.2. Comparative analysis of catchment area designs

Optimal catchment ditch widths (W_d) according to several authors in different slope-ditch geometric arrangements (Fig. 10) were compared. The results are summarized in Table 5 and Fig. 11. The comparison of these results suggests that the performance of the steepest triangular ditch of constant foreslope (used by Ref. [3] and this study) is more efficient (smaller W_d required) than the deep flat-bottom ditch model (proposed by Ref. [2] and Ref. [4]).

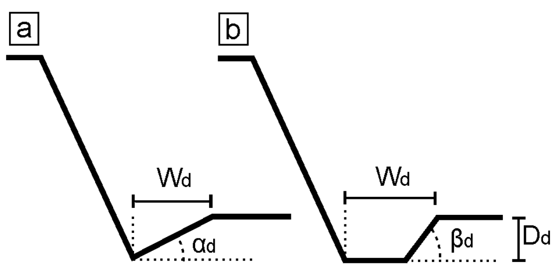

Fig. 10. Examples of topographic cross section modelled with diverse slope-ditch configurations: a) Ditch with foreslope steepness (Pierson et al., 2001; and this study); b) Trapezoidal ditch (Ritchie, 1963; Pantelidis, 2010). The values of each parameter are summarised in Table 5: (W_d) Ditch width; (α_d) Ditch steepness; (D_d) Ditch depth; (β_d) Ritchie´s ditch foreslope gradient.

Table 5

Comparative analysis of results for the optimal catchment area width (W_d) in eight slope-ditch geometric arrangements, according to different authors.

	H_t (m)	**12**				**24**			
	α_t (°)	**45°** (1H/1V)		**80°** (1H/6V)		**45°** (1H/1V)		**80°** (1H/6V)	
	α_d (°)	**0°** (1H/0V)	**14°** (4H/1V)	**0°** (1H/0V)	**14°** (4H/1V)	**0°** (1H/0V)	**14°** (4H/1V)	**0°** (1H/0V)	**14°** (4H/1V)
	Ref.	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
Ritchie (1963)	**D_d** (m)	1.5-1.8	-	1.2-1.5	-	1.8-2.1	-	1.5	-
	β_d	1/1.25	-	1/1.25	-	1/1.25	-	1/1.25	-
	W_d (m)	4.6	-	4.6-6.1	-	4.6-6.1	-	6.1-7.6	-
Pierson et al. (2001)	**W_d** (m)	15.5	4.3	7.3	4	21	8.5	7.3	5.2
Pantelidis (2010)	**D_d** (m)	1	-	1	-	1	-	1	-
	β_d	1/1	-	1/1	-	1/1	-	1/1	-
	W_d (m)	3	-	<3	-	8	-	3-5	-
This study	**W_d** (m)	2	1	4	3.5	2	1	2	1.5

(H_t) Slope height; (α_t) Slope gradient; (α_d) Ditch steepness; (β_d) Trapezoidal ditch foreslope; (D_d) Trapezoidal ditch depth; (W_d) Optimal ditch width; (Ref.) Reference of each geometric arrangement and W_d value represented in Fig. 11. Note: the slope gradient and ditch gradient are both expressed as the relation between horizontal [H] and vertical [V] distances (H/V)

It is worth noting that the optimal ditch width values (W_d) obtained in our work are significantly lower than the results from previous studies (Fig. 11). The percentage reduction of W_d in the present study in comparison to designs of previous authors varies over a wide range (12% to 90%) depending on the assumptions (Table 6). This could be related to the criterion assumed when modelling (random heights of launch points).

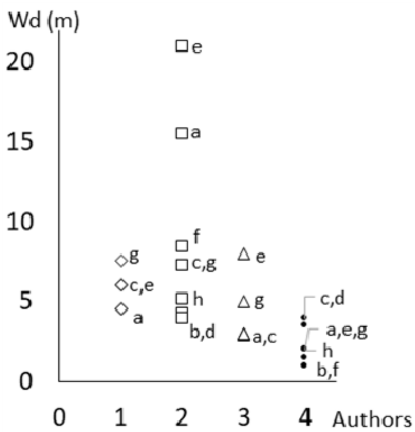

Fig. 11. Graphical representation of the optimal ditch width (W_d) values, according to different authors, summarised in Table 5. Authors: (1) Ritchie [1963]; (2) Pierson et al. [2001]; (3) Pantelidis [2010]; (4) This study.

Table 6

Summary of the percentage reduction of the optimal catchment ditch width (W_d) of the present study in comparison to the proposals of previous authors.

	Geometric arrangement (Ref. according to Table 5)							
Author	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
Ritchie (1963)	-56.5	-78.3	-34.4	-42.6	-67.2	-83.6	-73.7	-80.3
Pierson et al. (2001)	-87.1	-76.7	-45.2	-12.5	-90.5	-88.2	-72.6	-71.1
Pantelidis (2010)	-33.3	-66.6	+33.3	+16.7	-75.0	-87.5	-60.0	-70.0

Reduction of the optimal W_d (%) = (W_{d1}-W_{d2}) / (W_{d2}) x 100;
where: W_{d1}: optimal ditch width calculated in this study; W_{d2}: optimal ditch width calculated by previous authors.
Negative values indicate a percentage reduction, meaning that the optimal W_d proposed in this work is smaller.

The present study analyses rockfalls on homogeneous but anisotropic slopes with only one rock type and the same degree of alteration and weathering (RMR), because in volcanic materials the different main layers are usually sub-horizontal and with a thickness of tens of metres. Moreover, these assumptions allow to simplify modelling (summing up a total of 1,125 cases and 33,750 results). For rockfall modelling we assumed that launch points were randomly distributed along the entire slope. Other authors have preferred to consider exclusively launch positions located at the slope summit. However, the hypothesis proposed here encompasses the most common situations, because the probability of finding unstable blocks is similar along the entire slope under the assumptions aforementioned. Geotechnical studies suggest that rockfall launch locations are not always at the top of the slope, because they can be affected by several factors: e.g., the increase of horizontal stress against the slope wall towards the foot of the slope; amplification of instability due to undermining of a soft layer under a hard layer; accelerated weathering affecting the slope at points of aquifer discharge, etc. Thus, the hypothesis here proposed would allow more realistic technical studies to be drawn up and thus provide more economic solutions and more suitable to the service life of transport infrastructures.

4.3. Conceptual model of block accumulation in the catchment area

The statistical analysis of the absolute frequencies of blocks retained at each distance in the slope-ditch system establishes the block concentration areas depending on the ditch steepness and lithotype of rock. Results of roll-out stop-distances for the 1,125 cases analysed are available in a supplementary file (Table 7 in Electronic Supplementary Material).

For hard rock (HR) slopes in both ditch configurations (flat or foresloped ditches), statistical distribution of events shows a bimodal trend, with two areas of block concentration. Blocks tend to concentrate at the base of the slope (0-4 m) and between 7 to 9 m if the ditch presents a foreslope gradient. These distances increase nearly 2 m with a flat dich (Fig. 12).

On the contrary, in the case of soft rock lithotype (SR) the stop-distance distribution is unimodal in both ditch configurations and blocks are located at 95% below 4-5 m from de slope base (Fig. 12).

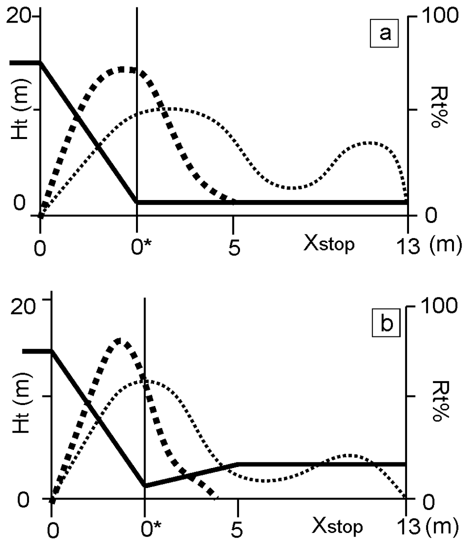

Fig. 12. Conceptual model of block retention distances for each lithotype (Hard rock, HR; Soft rock, SR). Representation of rock retention distribution (Rt%) related to the stop-distance (X_{stop}): a) Flat ditch configuration; b) Foresloped ditch. Note: the thickest dotted line represents the statistical distribution of blocks along the horizontal distance for SR, and the thinnest dotted line for HR.

5. Conclusions

Based on the results and discussion of this research, the following conclusions can be drawn regarding rockfall catchment area modelling and the factors involved:

- The material-related factors used in the simulation process (density D_b; hardness I_h; block roundness F_b; and block size S_b) show a direct correlation with the rockfall computer-simulated stop-distance (X_{stop}).
- The ditch steepness (α_d) presents an inverse relation with X_{stop}, meaning that steeper ditch foreslopes efficiently improve the retention capacity.
- However, the slope geometric factors (height H_t, gradient α_t) present uneven relations with X_{stop}. For hard rock lithotype (HR) and with the stop-distance retaining 95% of blocks (P_{95}), H_t has a direct correlation and α_t has inverse correlation, whereas with percentiles lower or equal than 50% the correlations are reversed. Numerical results suggest that the rockfall stop-distance is greater for intermediate slope gradients (45º-70º).
- For hard rock (HR) slopes, both with flat and with foresloped ditch, rock accumulation shows a bimodal statistical distribution, with two areas of block concentration. Blocks tend to concentrate at the base of the slope (0-4 m) and between 7 to 9 m if the ditch presents a foreslope gradient. These distances increases nearly 2 m with a flat dich. By contrast, in case of soft rock lithotype

(SR) the stop-distance distribution is unimodal in both ditch configurations and blocks are located below 4-5 m from de slope base.

- Factors related to rock hardness and strength (D_b, I_h) produce an amplification of the rockfall stop-distance (longer X_{opt} and bimodal distribution) and an increase of hazard associated with rockfall on infrastructures due to lower energy loss for blocks and inferior probability to be broken or fragmented. The effectiveness of the catchment area is then more evident at higher values of the ditch steepness.
- The slope geometric conditions are decisive for rockfall stop-distances. Re-excavation of the slope top or wider benches at half slope height with a foreslope gradient could increase the retention capacity of the slope-bench-ditch system. On the contrary, a flat and excessively narrow bench at half slope height could act as a sky jump board and make stop distances longer.
- The catchment area graphical design charts drawn up allow the determination of the suitable dimensions for ditches at the planning stage and also immediately evaluate the efficiency of the whole system (slope-ditch) for each geometric configuration, material properties and retention level assumed.
- A triangular ditch with constant foreslope steepness is more efficient than a deep flat-bottom ditch, and the former is more effective for the steepest gradient ($\alpha_d > 14º$). Furthermore, wider triangular ditches of less depth reduce the risk of vehicle overturning, increasing road safety, and simplifies ditch maintenance.
- The improved ditch design (reduction of catchment area width) proposed in this study compared to previous studies is associated with the criterion assumed when modelling (random nature of the launch point height). This assumed hypothesis is adequate for common and frequent geomechanical conditions, especially regarding volcanic geomaterials, and offers more economical and optimized solutions during the service life of transport infrastructures. These rockfall protection areas constitute non-structural defence measures with low environmental impact and reduced cost in volcanic territories.

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Supplementary material

Supplementary data associated with this article (Table 7 and Fig. 13) can be found in the online version.

Table 7. Statistical parameters of the X_{stop}* evaluated: (Ds) Standard Deviation; (H_t) Slope height; (K) Kurtosis Index; (M) Averaged value of X_{stop}*; (Ref) Reference code (see *1); (S) Skewness.

(*1) [Ht_(H:V)t_W_(H:V)d_L_Fb_Sb] Code to designate each evaluated arrangement according to its characteristic: (H_t) Slope height in m; $(H/V)_t$ Slope gradient expressed as the relation of horizontal and vertical distance; (W_d) Ditch width in m; $(H/V)_d$ Ditch foreslope expressed as the relation of the horizontal and vertical distance; (L) Lithotype: HR, Hard Rock; SR, Soft Rock; (F_b) Block shape (Cu, Cube; Sp, Sphere; Cy, Cylinder); (S_b) Block size.

Fig. 13. Graphic design charts for different slope-ditch configurations correlating the ditch width with the percentage of rock retention. Input parameters: (H_t) Slope height in m; $(H/V)_t$ Slope gradient expressed as the relation of the horizontal and vertical distance; Lithotype (HR, Hard Rock; SR, Soft Rock). The solid line represents a flat ditch (1H/0V), the dashed line a 10º ditch (6H/1V), and the dotted line a 14º ditch (4H/1V).