GEOMATICS AND ENVIRONMENTAL ENGINEERING • Volume 18 • Number 5 • 2024

https://doi.org/10.7494/geom.2024.18.5.75

Juan Manuel Pardo[1], Jose Miguel Galera[2], Joaquin Mulas[3]

# Methodology for Study of Rockfalls in Urban Areas – Computer Modeling and Mitigation in Algodonales, Spain

**Abstract:** Rockfalls in urban areas can cause significant damage. Without direct observation, it is difficult to reconstruct the specific details of an event. The study of rockfalls requires analyses of the source areas, slope parameters, blocks characteristics (size, shape, and mass), and the likely movements of independent blocks along their trajectories (free-falling, rolling, sliding, and rebounding). This article will propose a feasible methodology for the study of rockfalls based on identifiable parameters, conditioning factors (geology, geomorphology, geomechanical, hydrogeology, climate, and biology), and triggering factors (climate and dynamic loads). This article proposes the use of modeling programs to facilitate rockfall research and data management. The study of conditioning factors allows researchers to state several coefficients (restitution, surface roughness, rolling resistance, and friction) that one inputs into a modeling program, allowing researchers to obtain the representative results that are needed to design effective remedial measures. The methodology has been successfully applied to the urban area of Algodonales (Province of Cádiz, Spain).

**Keywords:** rockfall modeling, conditioning factors, triggering factors, protective barrier

Received: May 15, 2024; accepted: September 19, 2024

---

[1] Universidad Politécnica de Madrid (UPM), Escuela Técnica Superior de Ingenieros de Minas y Energía (ETSIMM); Geological Survey of Spain (IGME), Madrid, Spain, email: juan.pardo@alumnos.upm.es, jm.pardo@igme.es (corresponding author), https://orcid.org/0000-0002-5620-0496

[2] Universidad Politécnica de Madrid (UPM), Escuela Técnica Superior de Ingenieros de Minas y Energía (ETSIMM), Madrid, Spain, email: josemiguel.galera@upm.es, https://orcid.org/0000-0002-0218-4224

[3] Geological Survey of Spain (IGME), Madrid, Spain, email: j.mulas@igme.es, https://orcid.org/0000-0002-3201-0014

## 1. Introduction

Rockfalls are common risks on natural slopes; they may affect urban areas and endanger buildings, communication routes, etc. when they are located at toes of slopes. They can cause extensive damage, human losses, communications disturbances, and so on. The problem has not been thoroughly solved due to the diversity of the occurrences; each event requires an specific treatment and solution.

The trajectories of rockfalls can be obtained via experimentation, computational modeling, or empirical analysis. In recent years, several new rockfall trajectory simulation software programs have been developed, and the developments of drone applications and photogrammetric analysis have improved rockfall source area investigations [1–5].

Heim was the first scientist to describe rockfalls from a theoretical point of view [6]; however, the first practical approach to the design of remediation measures was established by Ritchie, who used field tests to design protective ditches and fences [7]. Broili analyzed large-scale rockfalls by studying the paths and behaviors of blocks, including the relationships among volumes, rebound heights, and ditch widths [8].

Other authors have used field tests to define and establish criteria for selecting active or passive protection methods [9]; however, there are disadvantages to field studies: they are time-consuming and expensive, their analytical results are limited to local conditions, and they pose risks of triggering rockfalls. Therefore, many scholars have developed simulation programs to assess rockfall hazards [10]. Regardless of the chosen program, accuracy in determining the restitution or damping coefficient is necessary [11]. This coefficient is critical and must be accurately evaluated based on experience and field trips.

**Fig. 1.** General view of Algodonales

Source: [13]

For this study, we used a 2D Rockfall simulation code; this code is based on rigid-body dynamics. The input data included the geometry of the rocks, the specific gravity of the rocks, and the coefficients of restitution, friction, rolling, and surface roughness [12].

This article focuses in the village of Algodonales in the Province of Cádiz, Spain (Fig. 1), as a case study. The village is located at the toe of a karst formation that is composed of calcareous rocks. The lithology is brecciated dolomite, dolomite, and dolomitic limestone from the Triassic and Early Jurassic periods [13].

## 2. Site Description

### 2.1. Geographical and Geological Settings

Algodonales is located at the toe of a karst hill in the Sierra de Líjar mountain range (with a 1,060 m elevation) (Figs. 2, 3). The rockfall source area is an irregular surface with dips of between 55° and 75°. The area's lithology consists of brecciated dolomite, dolomite, and dolomitic limestone. The slope is covered by debris-flow deposits with some isolated blocks of different sizes (Fig. 2) [13].

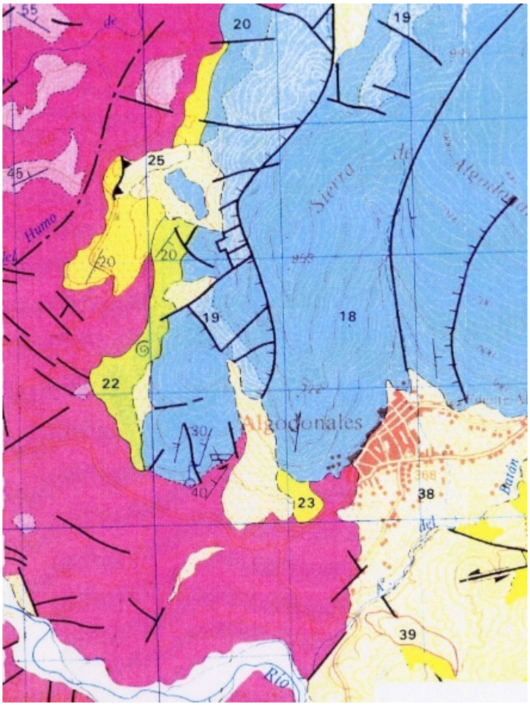

**Fig. 2.** Geological map of Algodonales (MAGNA 1:50,000), Section 18: massive dolomites

Source: [13]

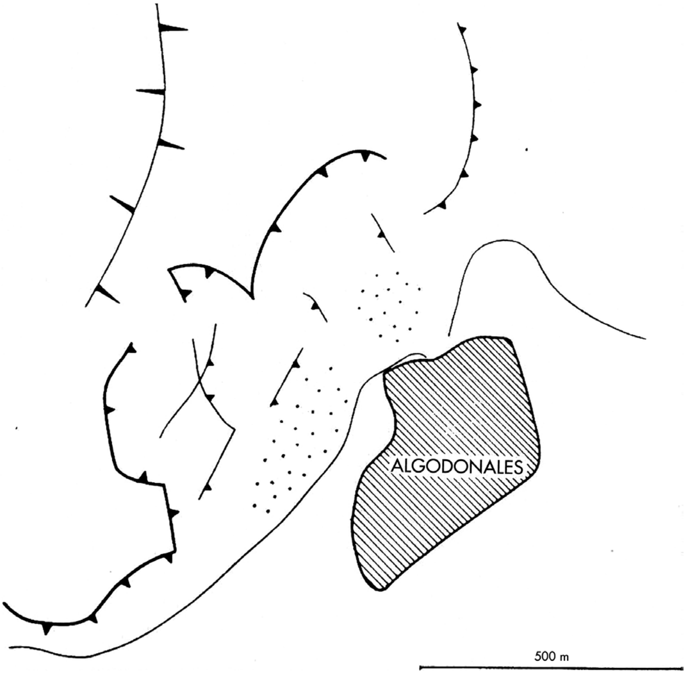

**Fig. 3.** Geomorphological map of Algodonales (main scarps and isolated blocks)

Source: [13]

The structure of the range is a large anticlinorium, with an ENE-WSW strike. The directions of the two main discontinuities that were involved in this study were E 60° S, N 30° E, and E 80° S [13].

The Sierra de Líjar aquifer is set into the karst and its internal network of cracks. The recharge of the aquifer is by rain infiltration, and the drainage mainly takes place in the contact between the clay materials and the carbonates. The permeability is considered to be $k = 10^{-6}$ m/s [14].

The climate is subtropical Mediterranean, with a warm thermal pattern. The average temperature is 17°, with an absolute minimum of –2° and an absolute maximum of 39° [13].

Vegetation is scarce, being composed of species that are adapted to a dry climate. The little residual soil is concentrated in the rock cracks and sinkholes; here, some trees and bushes have been able to grow. Anthropogenic action and fire have limited and modified the vegetation, facilitating weathering [13].

## 2.2. Geomechanics

Due to the difficulty of performing a direct shear test on intact rock, this study used geomechanical parameters that were drawn from several authors regarding similar carbonates (Table 1) [14–17].

**Table 1.** Geomechanical characteristics of rock

| Parameter | Value | Source |
|---|---|---|
| Uniaxial compressive strength | $q_u > 800$ kp/cm$^2$ | [14] |
| Young's modulus | $E > 50$ GPa | [14, 15] |
| Effective friction angle | $\varphi' = 37$–$50°$ | [14–17] |
| Effective cohesion | $c' > 50$ kg/cm$^2$ | [14–17] |
| Discontinuity peak conditions | $c' = 0$, $\varphi' = 33$–$37°$<br>(clean and unfilled)<br>$c' = 2$ kg/cm$^2$, $\varphi' = 13$–$14°$<br>(<1 mm clay infilled) | [15] |

The values are reasonable and consistent with those that could be found when they were cross-checked with the plot of the friction angles for the slopes (as identified by Hoek and Bray [18]).

## 2.3. Algodonales Rockfall Events

The hills around Algodonales are historic sources of rockfalls (Fig. 4). Several episodes that were related to heavy rainfall were reported between 1992 and 2013. One important rockfall event occurred on May 13, 1992, while another event (notable for involving large boulders) took place on September 12, 2006. Both events were related to heavy rainfall.

**Fig. 4.** Source area of rockfalls on slope above Algodonales

# 3. Analysis of Factors Involved in Rockfalls

## 3.1. Analysis of Conditioning Factors

The following will briefly analyze the conditioning factors that are involved in rockfalls.

### Geological Factor

The composition of a rock mass is closely related to its stability. Discontinuities divide the rock mass into blocks of intact rock according to the geological structure. Discontinuities have four important characteristics that determine the shapes and sizes of the blocks: orientation, position, length, and spacing [15]. The importance of describing and measuring these characteristics in the field cannot be overemphasized.

### Geomorphological Factor

Researching suggests that gravitational processes generally take place when the inclination of the slope exceeds 35° [19].

### Geomechanical Factor

Geomechanics play a role in the initiation of motion and the modeling of likely boulders running down the slope. Rocks are usually brittle and often full of preexisting cracks. The strength of a rock mass will depend on the properties and structure of its rock matrix and its discontinuities. The characteristics of the discontinuities (particularly its shear strength) are most likely to determine the behavior of the block, as breakage is most likely in discontinuity planes.

### Hydrogeological Factor

Water flowing through rock masses most often occurs in the discontinuities (secondary permeability). The presence of water in a rock mass decreases its stability via the following mechanism: decreasing shear strength due to the decreasing effective normal stress, increasing pressure over traction cracks, internal erosion due to underground water flow, weathering, mineral composition change, and new discontinuities that are caused by freezing water [14].

### Climate Factor

Weathering is the disaggregation and decomposition of surface geological materials. There are two kinds of weathering physical, and chemical that usually take place simultaneously: physical, and chemical. Climate determines which type of weathering is dominant. Physical weathering take place in dry climates (both warm and cold). Chemical weathering takes place in warm or temperate climates. Weathering affects a rock mass, its matrix and its discontinuities. Physical weathering can open new paths for water flow, thereby accelerating both the chemical and physical weathering.

**Biological Factor**

The absence of vegetation helps weathering [14]. Furthermore, the presence of trees or vegetation can disrupt the displacements of the blocks that run down the slope by acting as natural barriers.

### 3.2. Analysis of Triggering Factors

The following paragraphs will describe the main triggering factors in rockfalls.

**Climate Events**

The ground responds to heavy rainfall (storms) and wet or dry cycles over the course of one or multiple years. Water inside a slope causes increases in its weight, increases in its interstitial pressure, internal and external erosion, and mineralogical changes. Seasonal freeze-thaw cycles cause rockfalls in competent mass that is cracked by ice. By analyzing rainfall data from the days, weeks, and months before a rockfall, we can establish a rainfall threshold beyond which rockfalls become likely. Table 2 was extracted from a rainfall data set; it shows the threshold for triggering rockfalls by analyzing data series from 30–70 years in the past [14].

**Table 2.** Threshold rainfall for rockfall

| Type of movement | Rainfall by year [mm] | | Rainfall 3–4 months before rockfall [mm] | | |
|---|---|---|---|---|---|
| | total of previous year | annual average of series | total of previous months | total percentage of previous year [%] | annual percentage average of series [%] |
| Rockfall | 250–700 | 220–450 | 100–250 | ≤30 | 50–130 |

Source: [14]

**Dynamic Loads**

Natural or induced earthquakes can breakup rock or open up discontinuities, causing newly isolated blocks to fall. Nowadays, there is uncertainty about rockfalls that are induced by earthquakes. Keefer has shown that the earthquake-magnitude threshold for rockfall induction is $M_L = 4.0$ [20].

**Anthropic Factor**

Slope stability is reduced by overloads like buildings and structures, fill and waste disposal, etc.

**Biological Factor**

Plants and tree roots can open up cracks in rocks, and their movements can make a block unstable. The movement of animals over the slope is also a factor (to a lesser extent).

**Volcanism**

Eruptions can cause rockfall and avalanches.

## 4. Methods and Data

Rockfalls involve both the lithology and geomorphology of the rock. One (or a combination) of the following natural processes and climate features can contribute to the provocation of rockfalls: weathering discontinuities, freeze-thaw cycles, rainfall, plant-root growth, water input, and earthquakes [21–24].

This article analyzes the conditioning and triggering factors in the Algodonales region in order to determine a suitable remediation measure (in this case, a protective barrier). The methodology is illustrated in the diagram in Figure 5.

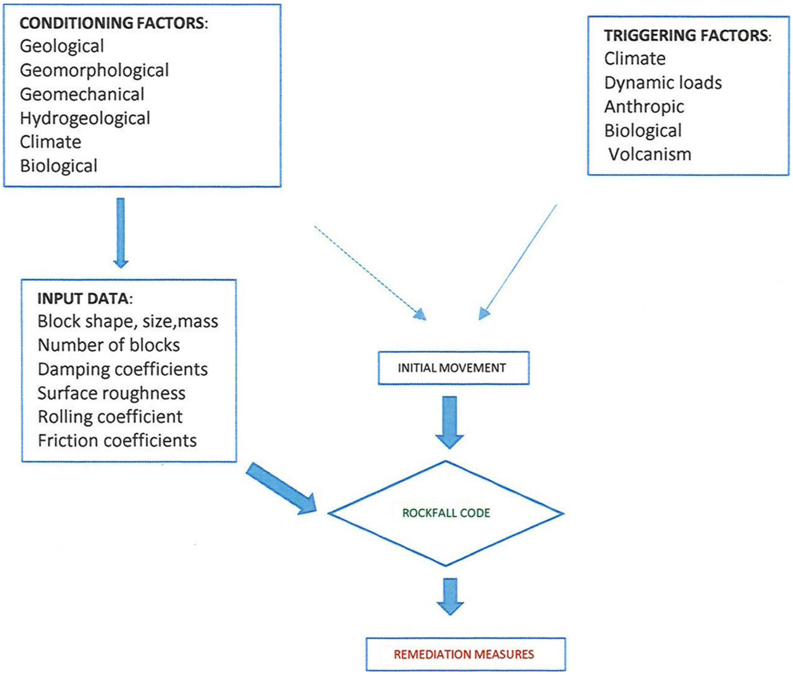

**Fig. 5.** Diagram of applied methodology

The following paragraphs will describe the data that is necessary for the computational modeling of rockfalls:

### Restitution or Damping Coefficient

The restitution or damping coefficient expresses the amount of energy that is released during impact. The maximum value is 1 (no energy released). The value decreases as the transmission of energy from the boulder to the slope increases. A value of zero means that there is no damping; the boulder does not rebound but rather stops. The value of this coefficient is related to the material composition of the input surface. Neat surfaces of hard rock have a high coefficient, while soil, gravel, and decomposed granite have low coefficients [25].

It is possible to separate the restitution coefficient into its tangential and normal components:

- the tangential restitution coefficient determines the velocity reduction parallel to the slope during impact; vegetation plays an important role in calculating the tangential coefficient;
- the normal restitution coefficient measures the changes in the normal velocity before and after an impact.

The values of both the tangential and normal restitution coefficients on slopes with a few meters of vegetation are difficult to evaluate, as the first rocks clear a path for those that follow (thus increasing the rebounds).

**Surface Roughness**

Generally, the rugosity of a slope is related to the sizes of the boulders on the slope. A rougher slope causes higher jumps in falling rocks; however, it results in a lower final velocity and decreased impact energy at the bottom.

**Rolling Coefficient**

In the cases of rolling or sliding, movement infers a loss of energy. From the dynamic point of view, rolling causes less surface exposure (and, thus, less energy loss). According to Bozzolo and Pamini [26], sliding occurs only at the beginning and end of an event (and only in the cases of large blocks).

**Coefficients of Friction**

The dynamic friction angle $R_h$ (in degrees) governs the friction between a boulder and the surface in the case of sliding. The range in the Rockfall modeling program varies between 0° and 89° [25]. The static friction angle $R_h$ (in degrees) – governs the friction between the boulder and the surface (in the case of static contact). The range of accepted input values varies between 0° and 89° [25]. The static friction angle must be greater than or equal to the dynamic friction angle.

Table 3 shows the values of the coefficients that were proposed by Spang [26] in the Rockfall 6.1 program.

**Table 3.** Table of coefficients that were proposed by Spang

| Surface type | Friction angle | | Damping factors [–] | | Rolling resistance [–] | Roughness | |
|---|---|---|---|---|---|---|---|
| | dynamic [°] | static [°] | normal | tangential | | amp. [m] | freq. [m] |
| Rock – mainly smooth surface | 30 ±5% | 40 ±5% | 0.060 ±10% | 0.930 ±8% | 0.020 ±10% | 0.10 | 1.00 |
| Rock – rough surface | 30 ±5% | 40 ±5% | 0.060 ±10% | 0.930 ±8% | 0.050 ±15% | 1.00 | 2.00 |
| Rock – debris-covered or wooded | 25 ±5% | 35 ±5% | 0.050 ±15% | 0.900 ±10% | 0.080 ±15% | 0.50 | 1.00 |
| Rock – with thin soil cover | 15 ±5% | 30 ±5% | 0.035 ±20% | 0.800 ±10% | 0.100 ±15% | 0.20 | 1.00 |
| Rock – debris with thin soil cover | 15 ±5% | 35 ±5% | 0.040 ±15% | 0.850 ±15% | 0.150 ±15% | 1.00 | 1.00 |
| Residual soils – grass-covered | 15 ±5% | 30 ±5% | 0.030 ±10% | 0.750 ±10% | 0.120 ±15% | 0.10 | 1.00 |

## 5. Application to Case of Algodonales

After the rockfall of May 13, 1992, a geological survey of Spain began a detailed study of the hillside. Eight slope profiles were identified for this study (Fig. 6).

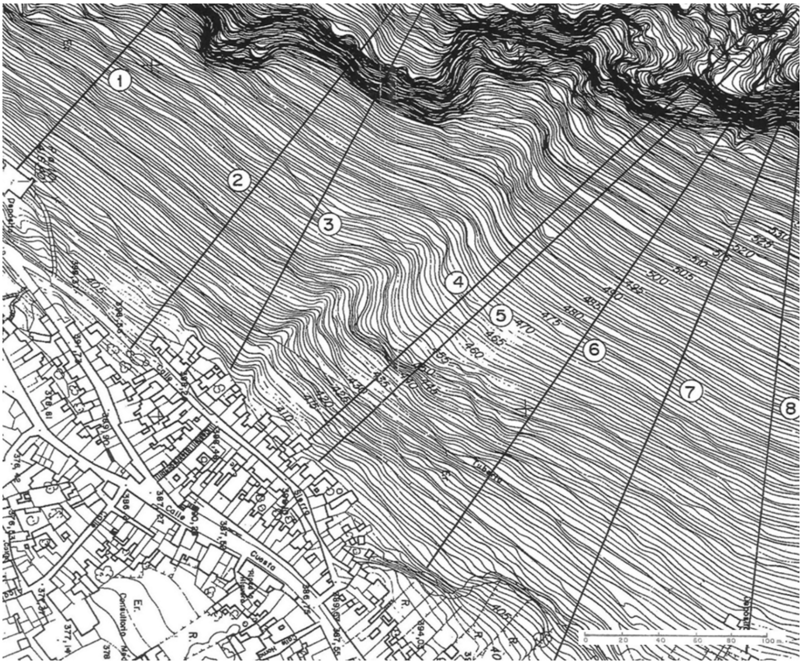

**Fig. 6.** Algodonales profiles
Source: [13]

A lumped-mass model, which considered only the mass – not the size – of the falling rock, was used to study the 1992 event. For this purpose, a code called R2 was developed using BASIC. This software includes the coefficient of restitution and friction but excludes the surface-roughness and rolling coefficients.

During the 2006 event, 1,000-kilogram boulders were reported in the proximity of the Profile 3 trajectory and reached several houses below. To study the event, the rigorous rigid-body Rockfall 6.1 modeling program was used with new calculations. It provided more-accurate results than the R2 program did.

The following paragraphs describe the steps that are needed to study the Algodonales slope in order to obtain the final results that allow for the design of a suitable rockfall barrier.

**Conditioning Factors in Algodonales**

A comprehensive analysis of the conditioning factors allows for a definition of the physical characteristics of a likely block falling down the slope (Table 4).

**Table 4.** Input data regarding blocks physical characteristics, number of rocks, and initial conditions

| Parameter | Value |
|---|---|
| Number of rocks | 50 |
| Radius [m] | 1.06 |
| Mass [kg] | 12,472.29 |
| Initial motion | rolling/sliding |
| Initial position $X$ [m] | 0.00 |
| Delta $T$ [s] | 0.02 |
| Normal velocity $V_{grN}$ [m/s] | 0.05 |
| Tangensial velocity $V_{grT}$ [m/s] | 0.05 |

**Triggering Factors in Algodonales**

Climate: during the three months preceding the May 13, 1992, rockfall, 154 mm of rain was recorded. This value exceeded the threshold for rockfall triggering (Table 2).

Dynamic loads: the basic seismic acceleration in the area of Algodonales is $a_g = 0.08$ g according to the Spanish Seismic Code [27]. This value exceeds the minimum threshold that is needed for slope stability [28].

**Algodonales Data**

This study input the coefficients that were proposed by Spang [25] into the Rockfall 6.1 modeling program. Even though we have eight established slope profiles in Algodonales, we selected Profile 3 for a detailed study because, according to an earlier field examination of falling blocks, its path is the most likely to affect buildings. Profile 3 (Fig. 6) was divided into three slices, and different values were used for the slices considering the different characteristics of the slope: first, a rough surface; then, a thin soil cover in the third slice (Table 5).

**Table 5.** Values of physical coefficients that were used in Algodonales

| $x(0)$ | Slices $x_e$ [m] | Friction angle | | Damping factors [–] | | Rolling resistance [–] | Roughness | |
|---|---|---|---|---|---|---|---|---|
| | | dynamic [°] | static [°] | normal | tangential | | amp. [m] | freq. [m] |
| 0 | 80 | 30 ±5% | 40 ±5% | 0.060 ±10% | 0.930 ±7% | 0.050 ±15% | 1.00 | 2.00 |
| 80 | 115 | 30 ±5% | 40 ±5% | 0.060 ±10% | 0.930 ±7% | 0.050 ±15% | 1.00 | 2.00 |
| 115 | 280 | 15 ±5% | 30 ±5% | 0.035 ±20% | 0.800 ±10% | 0.100 ±15% | 0.20 | 1.00 |

## 6. Results

Once we identified the source area using field trips and aerial photography, we analyzed the conditioning factors, determining the density, size and shape of the boulder.

The first approach to the problem, how was explained on paragraph 5, was a BASIC code named R2. Considering a 220 m slope with a dip of 45°, a damping coefficient of 0.5 and a single block of 1,040 kg. After 11 rebounds, the energy value was equal to 438 kJ near at the toe of the slope despite the lack of some factors, like surface roughness (Table 6).

**Table 6.** Results of R2 code

| Input values | | Output values* | |
|---|---|---|---|
| Longitude of slope | $L = 220$ m | Final velocity of boulder | $v_f = 29$ m/s |
| Dip of slope | $D = 45°$ | Longitude of slope | $L_f = 138$ m |
| Mass of boulder | $m = 1040$ kg | Kinetic energy of boulder | $Ec = 438$ kJ |
| Coefficient of restitution | $e = 0.5$ | | |
| Coefficient of friction | $f = 0.25$ | | |
| Initial incident angle of boulder | $O = 36°$ | | |
| Initial velocity of boulder | $v_0 = 20$ m/s | | |

* after 11 rebounds.

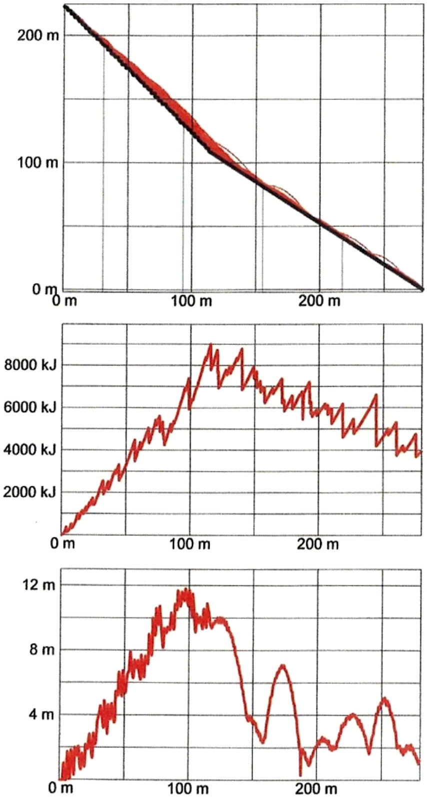

**Fig. 7.** Envelope curve: total kinetic energy $Ec$ and bounce height (Profile 3)

We considered it to be more appropriate to employ the more robust Rockfall 6.1 code on the next rockfall study. This code allowed two boulder shapes: sphere, or cylinder. The sphere shape was deemed to be more appropriate in this case (Table 4).

The results of the analysis are shown in Figure 7.

The highest rebound and peak energy were reached 100 m below the top of the slope; thus, this point would be the optimal location for a barrier that is able to retain those boulders that arrive with energy values of around 5,000 kJ.

## 7. Discussion and Conclusions

After analyzing the current best practices regarding rockfall studies and mitigation, the objectives were to establish a feasible methodology that facilitated the study of the phenomenon as well as the factors and parameters that were needed to establish such a methodology; this involved the use of the Rockfall code (in this case, it is one of the most suitable codes due to its rigor and versatility). Considering the parameters that were input into the code, we were especially careful when identifying normal restitution coefficient (which is a critical parameter). To remark on this, a comparison of the results that were obtained with the lumped R2 mass model (summarized in Section 5) with those that were obtained by the more rigorous Rockfall 6.1 program found that both were reasonable but that Rockfall 6.1 represented a notable improvement (R2 only considers the damping or restitution coefficient parameter, thereby obtaining an energy value of 438 kJ for a block with a mass of 1,040 kg near the foot of a slope). The values were considered to be representative and acceptable for a block of this size, but we needed to establish some parameters and conditions that were not easily to acquire (like the initial conditions or limiting the number of rebounds) by performing a trial-and-error exercise. On the other hand, Rockfall 6.1 considers more parameters and provides rebound heights; the program determined that an optimal barrier must be able to retain blocks with a mass of 10,000 kg and an energy value of 5,000 kJ.

Rockfall 6.1 also allows researchers to simulate the fall of several boulders at once; this is not standard across similar programs. This study simulated the fall of 50 boulders. Even though these researchers did not have enough information to do so, the program even allowed for the possibility of simulating the fragmentation of boulders on their paths down a slope.

Ultimately, 6.1 facilitated the successful design of rockfall barriers as remedial measures. This is useful in many cases (like with Algodonales, where rockfall barriers are the most effective remedial measure). Rockfall 6.1 gives us the outputs that are necessary to design the barriers.

Rockfalls are a normal consequence of slope evolution. This article has established a feasible methodology to systematize the study of rockfalls, reducing the required time and costs and avoiding field or laboratory tests. We applied the proposed methodology to the real-world case of Algodonales, thereby validating its success and utility.

**Funding**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**CRediT Author Contribution**

J. M. P.: conceptualization, methodology, writing.
J. M. G.: supervision.
J. M.: supervision, data curation.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

**Data Availability**

Public data: Geological Survey of Spain (Instituto Geológico y Minero de España, IGME).

**Use of Generative AI and AI-assisted Technologies**

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

**Acknowledgements**

Thank you to the Geological Survey of Spain which was facilitated this research.

## References

[1] Leine R.I., Schweizer A., Christen M., Glover J., Bartelt P., Gerber W.: *Simulation of rockfall trajectories with consideration of rock shape*. Multibody System Dynamics, vol. 32(2), 2014, pp. 241–271. https://doi.org/10.1007/s11044-013-9393-4.

[2] Massaro L., Forte G., De Falco M., Rauseo F., Santo A.: *Rockfall source identification and trajectory analysis from UAV-based data in volcano-tectonic areas: a case study from Ischia Island, Southern Italy*. Bulletin of Engineering Geology and the Environment, vol. 83(3), 2024, 75. https://doi.org/10.1007/s10064-024-03569-1.

[3] Sari M.: *Evaluating rockfalls at a historical settlement in the Ihlara Valley (Cappadocia, Turkey) using kinematic, numerical, 2D trajectory, and risk rating methods.* Journal of Mountain Science, vol. 19(12), 2022, pp. 3346–3369. https://doi.org/10.1007/s11629-022-7412-8.

[4] Sarro R., Riquelme A., García-Davalillo J.C., Mateos R.M., Tomás R., Pastor J.L., Cano M., Herrera G.: *Rockfall simulation based on UAV photogrammetry data obtained during an emergency declaration: Application at a cultural heritage site*. Remote Sensing, vol. 10(12), 2018, 1923. https://doi.org/10.3390/rs10121923.

[5] Topal T., Akin M., Ozden U.A.: *Assessment of rockfall hazard around Afyon Castle, Turkey*. Environmental Geology, vol. 53(1), 2007, pp. 191–200. https://doi.org/10.1007/s00254-006-0633-2.

[6] Heim A.: *Ueber Bergstürze*. Verlag von J. Wurster & Cie, Zürich 1882.

[7] Ritchie A.M.: *Evaluation of Rockfall and Its Control*. Highway Research Record, No. 17, Highway Research Board, Washington, D.C., 1963, pp. 13–28. http://onlinepubs.trb.org/Onlinepubs/hrr/1963/17/17-002.pdf.

[8] Broili L.: *Ein Felssturz im Grossversuch*. [in:] Müller-Salzburg L. (ed.), *Felsmechanische Grundlagenforschung Standsicherheit von Böschungen und Hohlraumbauten in Fels / Basic Research in Rock Mechanics Stability of Rock Slopes and Underground Excavations,* Rock Mechanics / Felsmechanik / Mécanique des Roches, vol. 3. Springer, Vienna 1974, pp. 69–78. https://doi.org/10.1007/978-3-7091-8372-4_9.

[9] John K.W., Spang R.M.: *Steinschläge und Felsstürze: Voraussetzungen – Mechanismen – Sicherungen*. Vortrag UIC-Tagung, Kandersteg 1979.

[10] Tang J., Zhou X., Liang K., Lai Y., Zhou G., Tan J.: *Experimental study on the coefficient of restitution for the rotational sphere rockfall*. Environmental Earth Sciences, vol. 80(11), 2021, 419. https://doi.org/10.1007/s12665-021-09684-6.

[11] Chau K.T., Wong R.H.C., Liu J., Wu J.J., Lee C.F.: *Shape effects on the coefficient of restitution during rockfall impacts*. Paper presented at the 9th ISRM Congress, Paris, France, August 1999, ISRM-9CONGRESS-1999-111.

[12] Spang R.M.: *Protection against rockfall – Stepchild in the design of rock slopes*. Paper presented at the 6th ISRM Congress, Montreal, Canada, August 1987, ISRM-6CONGRESS-1987-101.

[13] *Estudio sobre el desprendimiento de rocas en la localidad de Algodonales (Cádiz).* Code 01295, The repository of Geological Survey of Spain (Instituto Tecnológico Geominero de España, ITGE).

[14] González de Vallejo L.I., Ferrer M.: *Engineering Geology*. CRC Press, London 2011. https://doi.org/10.1201/b11745.

[15] Duncan C.W.: *Foundations on Rock*. Chapman & Hall, London 1992.

[16] Rahn P.H.: *Engineering Geology: An Environmental Approach*. Elsevier, 1986.

[17] Walthan A.C.: *Foundations of Engineering Geology*. E & FN Spon, London – New York 1999.

[18] Hoek E., Bray J.: *Rock Slope Engineering*. 3rd ed. Institution of Mining and Metallurgy, London 1981.

[19] Jaeger Ch.: *Rock Mechanics and Engineering*. Cambridge University, Press 1972.

[20] Keefer D.K.: *Landslides caused by earthquakes*. Geological Society of America Bulletin, vol. 95(4), 1984, pp. 406–421.

[21] Bozdağ A.: *Rockfall hazard assessment in a natural and historical site: The case of ancient Kilistra settlement (Konya), Turkey*. Journal of Mountain Science, vol. 19(1), 2022, pp. 151–166. https://doi.org/10.1007/s11629-021-6961-6.

[22] Kanari M., Katz O., Weinberger R., Porat N., Marco S.: *Evaluating earthquake-induced rockfall hazard near the Dead Sea Transform*. Natural Hazards and Earth System Sciences, vol. 19(3), 2019, pp. 889–906. https://doi.org/10.5194/nhess-19-889-2019.

[23] Schilirò L., Massaro L., Forte G., Santo A., Tommasi P.: *Analysis of earthquake-triggered landslides through an integrated unmanned aerial vehicle-based approach: A case study from Central Italy*. Remote Sensing, vol. 16(1), 2024, 93. https://doi.org/10.3390/rs16010093.

[24] Santi P.M., Russell C.P., Higgins J.D. Spriet J.I.: *Modification and statistical analysis of the Colorado Rockfall Hazard Rating System*. Engineering Geology, vol. 104(1–2), 2009, pp. 55–65. https://doi.org/10.1016/j.enggeo.2008.08.009.

[25] Spang R.M.: *Rockfall 6.1 Manual*. March 2003.

[26] Bozzolo D., Pamini R.: *Simulation of rock falls down a valley side.* Acta Mechanica, vol. 63(1–4), 1986, pp. 113–130. https://doi.org/10.1007/BF01182543.

[27] *Norma de Construcción Sismorresistente: Parte General y Edificación (NCSE-02).* Boletín Oficial del Estado, 11.10.2002, Núm. 244, Agencia Estatal Boletín Oficial del Estado, Madrid 2002. https://www.boe.es/eli/es/rd/2002/09/27/997/dof/spa/pdf.

[28] Wilson R.C., Keefer D.K.: *Predicting a real limits of earthquake-induced landsliding.* [in:] Ziony J.I. (ed.), *Evaluating Earthquake Hazards in the Los Angeles Region – An Earth-science Perspective*, Professional Paper, no. 1360, U.S. Geological Survey, Reston, Virginia, 1985, pp. 317–345.