Rockfall and Rainfall Correlation in the Anaga Nature Reserve in Tenerife (Canary Islands, Spain)

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Abstract
Rockfalls are frequent and damaging phenomena that occur on steep or vertical slopes, in coastal areas, mountains and along coastal cliff. Water, in different forms, is the most common triggered factor of rockfalls. Consequently, we can consider that precipitation is the most influential factor for slope instabilities and it influences almost all other water parameters. Besides, the specific geology of the Anaga nature reserve in the volcanic island of Tenerife, together with its steep landscape, contributes to the instability of the slopes and frequent rockfalls. Recently, due to climate change and global warming, the annual precipitation/rainfall has declined but the number of heavy storms, associated with intense rainfall and strong winds, events that exceed precipitation thresholds in a brief period has increased which triggers slope movements. This paper describes the analysis of information on rainfall-induced rockfalls in Anaga, Tenerife (Canary Islands), to forecast rock failures of social significance and to improve the capability to respond and emergency decision making. To define reliable thresholds for a certain area, we analyzed information during the period 2010–2016, reconstructed the rockfall events, and statistically analyzed the historical rainfall conditions that led to landslides. The summary graph correlating precipitation to the probability of occurrence of an event was plotted. Statistical and probability graphs were made with the direct relationship between the number of rockfall events and total rainfall in that period by examining the maximum daily precipitation, not only on the day of the event but up to 3 days before. Hence, the results of this study would serve as a guide for the possible forecasting of rainfall-induced rockfalls, especially for road maintenance services, so that they can be on alert or mobilize the necessary resources in advance depending on the intensity of the expected rainfall.

Highlights
• We have determined the correlation between the probability of occurrence of a rockfall event in a natural reserve (Anaga, island of Tenerife, Canary Islands) and the expected rainfall intensity.
• We have observed the time delay between the occurrence of rainfall and rock falls, corroborated by experience in this area, between the day of the event and the day of the maximum rainfall associated with it.
• We have provided a tool to be used by the Civil Protection and Emergency and Road Maintenance and Conservation Services of the island of Tenerife as part of their management to mobilize the necessary resources or means or to adopt traffic limitations or restrictions depending on the level of alert decreed for adverse meteorological phenomena related to rainfall.

Keywords Rockfalls · Canary Islands · Road services · Geological risks · Rainfall episodes
1 Introduction

Rockfalls are, by definition, a type of landslide involving abrupt downward movement of rock or soil, or both, that detach from steep slopes or cliffs (Highland and Bobrowsky 2008). The falling mass may break on impact, start rolling on steeper slopes, and continue rolling until the terrain flattens. Rockfalls are frequent and damaging phenomena that occur on steep or vertical slopes, in coastal areas, mountains, and along rocky banks of rivers and streams (Langping and Hengxing 2015). The volume of material in a rockfall can vary considerably, from individual rocks or clumps of soil to massive blocks thousands of cubic meters in size (Margottini et al. 2013).

Water, whether it is solid water (ice, snow), whether it is in liquid form such as rain, groundwater, melting ice, etc.; or whether it is water pressure, water energy (undercutting of slopes by natural processes such as streams, rivers, and ocean/sea waves), seismic activity, or anthropogenic activities (burst water pipes, and similar), etc., is the most common cause of rockfalls (Ansari et al. 2015; de Vallejo et al. 2020a, b; Hibert et al. 2011; Hürlimann et al. 1999; Keefer 2002; Mateos et al. 2020; Saroglou 2019; Uchimura et al. 2010; Wieczorek and Jäger 1996).

At regional scales, empirical approaches to forecast the occurrence of rainfall-induced landslides depend on accuracy defining rainfall thresholds. In recent years, several authors have proposed different methods for calculating rainfall thresholds through statistical analysis of empirical triggering rainfall distributions. These methods include cumulative rainfall amount versus rainfall duration, or average rainfall intensity versus rainfall duration. However, these precipitation thresholds include numerous uncertainties that limit their application in early warning systems (Rosi et al. 2020; Melillo et al. 2018; Guzzetti et al. 2020).

The empirical estimation of precipitation thresholds is affected by different uncertainties linked to: (i) the availability of quality information concerning rainfall measurements, with numerous parameters of intensity, duration, daily and even hourly data; (ii) the existence of a good inventory of rockfalls that have occurred, specifically with the date of their occurrence; (iii) the characterization and identification of the rainfall event responsible for the landslide. For this reason, it is difficult to find in the literature case studies with a good definition of the triggering rainfall thresholds. However, we can consider that rainfall is the factor that most influences the instability of the slopes, and it can influence almost all the other water parameters mentioned above (Ayonghe et al. 1999; Contino et al. 2017; Vessia et al. 2020). In addition, there is a great danger from rockfalls triggered by rain, especially on volcanic, unstable slopes (Barbano et al. 2014; Kimura and Kawabata 2015; Smerekanicz et al. 2008). Furthermore, evidence of the major influence of rain was provided in the previous study developed in the island of Tenerife by Jiménez and García-Fernández (2000). The study concluded that there is a correlation, with more than 99% certainty, between intense rainfall periods and the temporal distribution of local microearthquake activity in Tenerife.

Moreover, climate change poses risks to human and natural systems, and the processes of slope instabilities are part of those risks (Komori et al. 2018; Lollino et al. 2015). The result of climate change and global warming is less rainfall in annual rainfall count, but at the same time there are more severe weather events that exceed precipitation thresholds and trigger slope movements, so there will be an increase in precipitation in concentrated events (Luo et al. 2017; Mateos et al. 2020). Although both factors have an influence, for triggering the mechanisms of soil and rock breakage that move the material on the slopes, exceeding the precipitation thresholds (punctual intense precipitation) is more important than the number of days of rainfall per year (accumulated annual precipitation) (Bello-Rodríguez et al. 2019; Hendrix and Salehyan 2012; Hernández González et al. 2016; Hernández et al. 2018).

In order to define reliable thresholds for a certain area, we need to reconstruct the rockfall events and statistically analyze the historical rainfall conditions that caused landslides. The data should serve as a guide for the possible prediction of rainfall-induced rock slides.

Rock curtains or other slope covers, protective covers over roadways, retaining walls to prevent rolling or bouncing are used to mitigate unstable slopes. Although rock bolts or other similar types of anchoring are used to stabilize cliffs, some landslides cannot be mitigated, making the importance of predicting failures even greater (Gutiérrez et al. 2010; Mateos et al. 2020). Primarily for the safety of the inhabitants but also for preserving infrastructures such as roads and buildings. (Guzzetti et al. 2007, 2008; Miklin et al. 2016; Peruccacci et al. 2017; Valenzuela et al. 2018, 2019; Venelli et al. 2014).

When it comes to protecting human lives, there can never be sufficient research to ensure safety and prevent catastrophic events. For Gran Canaria and Tenerife (Canary Islands) a research group of the Research Institute for Geohydrological Protection (IRPI) and the Geological Survey of Spain (IGME) analyzed rainfall-induced rockfalls based on CTRL-T algorithm exploiting continuous rainfall measurements, and landslide information (Melillo et al. 2020). Therefore, in this article, we will show a new advance about correlation of rockfall and rainfall events from a historical-statistical perspective in the area of Anaga, Tenerife.
1.1 Study Area: Anaga, Tenerife (Canary Islands, Spain)

The Canary archipelago in the Atlantic Ocean consists of eight islands with a total area of about 7500 km². Tenerife is the largest (2057 km²) and the most populated (966,000 inhabitants and 13.2 million visitors in 2019) island in the center of the Canary archipelago (Fig. 1) (data from the Spanish National Statistical Institute).

Tenerife not only occupies a central position within the archipelago but also represents an intermediate evolutionary stage relative to the eastern and the western islands of the island chain. It is home to the third-largest volcano in the world, Pico del Teide. If you take the seafloor as the base of the volcano and not the sea level, then the Teide rises more than 7000 m in height (3718 masl) (Melillo et al. 2020; Troll and Carracedo 2016).

Tenerife is mainly a basaltic shield, which represents about 90% of the volume of the island (Hürlimann et al. 1999). It lies on the Jurassic (150–170 Ma) oceanic lithosphere and was constructed via Miocene–Pliocene shields that now form the vertices of the island (Fullea et al. 2015). The shields were unified into a single edifice by later volcanism that continued in central Tenerife from about 12 to 8 million years ago and was followed by a period of dormancy. Rejuvenation at approximately 3.5 Ma is recorded by the central Las Cañadas volcano. During this period magmatic differentiation processes occurred, leading to an episode of felsic and highly explosive felsic volcanism (Fig. 1) (Martí and Wolff 2000; Troll and Carracedo 2016).

The Anaga massif belongs to Series I (Middle–Upper Miocene) and, due to erosion, this massif currently has a steep orography (Fig. 2) with steep slopes (Marinonia and Gudmundssonb 2000). The natural reserve of Anaga is a protected area due to its richness in flora and fauna, as well as archaeological sites (Jiménez-Gomis et al. 2019). The orography and altitude favor rainfall in this area of the island, a phenomenon that increases the probability of rock falls in Anaga (Fig. 3).

The Anaga massif has an average altitude of 850 m above sea level and, in addition, a phenomenon known as the “Foehn effect” occurs here, which is produced by the warm, humid winds that blow frequently from the northwest to northeast, producing a layer of stratocumulus on the higher ground, often accompanied by drizzle (Santana 2014). Subsequently, the air descends, losing its watery content on the opposite slope. This causes a constant humidity in Anaga, which leads to the capture of horizontal precipitation that
produces the Foëhn phenomenon (Kalivodová et al. 2020). Therefore, the geographical situation of Anaga, located in the northeast of Tenerife, its altitude and the constant humidity on the slopes, make this area of Tenerife one of the areas with the highest rainfall compared to the rest of the island (Diez-Sierra and del Jesus 2020).

High gradient slopes spread over large areas of the islands, and two antagonistic processes are involved in their formation, namely erosion and the formation of lavas, scoria, and pyroclastic layers. Erosion or mass wasting processes occur on previously unstable slopes. Thus, the northern part of the island is characterized by narrow and deep ravines that contribute to intense slope activity (del Potro and Hürlimann 2008; Melillo et al. 2020). Usually, these landscapes are associated with the oldest basaltic outcrops of the islands (along the deep ravines and coastal cliffs of the “Anaga” and “Teno” massifs, the wall of the “Cañadas” caldera, head and edges of the “Güímar” and “La Orotava” valleys in Tenerife Island) (Fig. 1). In these locations the slopes dip at angles ranging from 50° to 65° and from 26° to 30° and are nearly vertical in the cliff areas. Most of these areas are the result of earlier landslides and consequently, there is an early occurrence of large mass wasting processes (González de Vallejo et al. 2008; Ledo et al. 2015). The accumulation of volcanic lava flows and interbedded pyroclastic layers is the result of cycles of continuous volcanic eruptions that can result in the the build-up of large steeped edifices with poorly stabilized slopes and high risk of landslides. The growth of such unstable volcanic edifices may occur over previously collapsed areas, filling the resulting deeply eroded depressions prone landslides. Steep slopes created by the accumulation of lavas and pyroclasts are thought to be zones of potential landslide hazard. An example of these steep areas is the “Teide stratovolcano”, whose flank inclination varies from 25° to 30°. Teide has slopes higher than 1000 m and conditions close to the limit where the slope gradient exceeds the friction angle of their rock massifs (del Potro and Hürlimann 2008; Martí and Wolff 2000; Rodríguez-Losada et al. 2009). These areas can be prone to extremely large landslides if cohesion decreases rapidly. The decrease can be due to shallow magma injection, fluid injection, or groundwater pressure (Herrera and Custodio 2014; Kimura and Kawabata 2015; Rodríguez-Losada et al. 2009). Additional factors such as pre-existing fracture zones also increase the risk of landslides (Hibert et al. 2011).

The steep orography and climatic diversity of Tenerife have resulted in a variety of landscapes and geographical formations. The climate of Tenerife is subtropical oceanic; the minimum and maximum annual average temperatures are about 15 °C in winter and 24 °C in summer. The annual rainfall ranges from 100 to 900 mm, being the northern slope the one that receives the highest volume of rainfall, as can be seen from the following image taken from the document CLIMCAN-010 of the Government of the Canary Islands (Fig. 4). Besides, Tenerife offers a wide variety of
microclimates controlled by altitude and winds (Bechtel 2016; Hernández González et al. 2016; Köhler et al. 2006).

2 Methodology

The methodology followed for data collection was:

1. Collect data on all events classified as “Rockfalls” that occurred during the period 2010–2016 (specifically from 01/08/2010 to 05/05/2016) that were addressed by the personnel assigned to the Contracts of Integral Conservation of Roads (North, South, West and Anaga Sectors), promoted by the Cabildo Insular de Tenerife and conducted by external companies. This information was compiled from the management system implemented in the Organic Unit of Integral Conservation (Cabildo de Tenerife), through the computer application GCC 2.2 “Gestor de Conservación de Carreteras Versión 2”.

2. The representativeness of the data in relation to the totality of the administered roads (Insular and of Regional Interest), a total of 584 kms was included out of the estimated total of 1378 kms that in that period were available in the entire island (Table 1). However, all the most important main roads of the island (highways, multi-lane roads and conventional roads with the highest traffic) are included; thus, their representativeness of the island’s road infrastructure is considered as sufficient.

3. Review of all the reports of incidents collected, checking through the attached graphic information for possible

Table 1 Total kilometers of road in the island of Tenerife

| Zone            | Km  | % of total |
|-----------------|-----|------------|
| Ordinary maintenance |     |            |
| North           | 361 | 26.18%     |
| South           | 250 | 18.13%     |
| Center          | 183 | 13.31%     |
| Integral conservation |   |            |
| Anaga           | 96  | 6.98%      |
| West            | 97  | 7.02%      |
| North           | 183 | 13.26%     |
| South           | 208 | 15.13%     |
|                 | 1378| 100%       |
errors, as well as the magnitude of the event, discarding for the study those related to very small surface detachments and with no effect on traffic.

4. Compilation of all meteorological data during that period (2010–2016) from all existing raingauges in the study area. The information published by AEMET\(^1\) and AgroCabildo\(^2\) was used, selecting the gauge closest to each incident.

5. Study the relationship between events and precipitation by calculating probabilities. In the case of Anaga Sector, due to previous experience, it was known that there was a certain delay between the day on which the precipitation occurred and the day on which the event occurred. Therefore, the study was done by checking the maximum daily precipitation, not only on the day of the event, but up to 3 days before.

### 3 Results and Discussion

Figure 5 shows the summary graph of the statistical study conducted on the relationship between the daily level of precipitation and landslide events occurring on the roads of the Anaga Sector.

A significant observation is the delay between the day of the event and the day the maximum precipitation occurred, up to a maximum of 3 days before the event. The results indicate:

- 39% of the maximum precipitation took place on the day of the landslide;
- 26% the day before;
- 15% two days before;
- 20% three days before.

Therefore, only 40% of the events seem to be associated with the maximum precipitation occurring on the day of the landslide. This fact corroborates the experience in this Sector, which confirms that after an episode of rainfall of a certain intensity, events tend to occur not only on the same day but also on the following days without new rainfall in most cases.

Figure 6 shows the total number of events in Anaga and the monthly accumulated rainfall. Thus, the results highlight the direct relationship between the number of events and the total amount of rainfall in that period.

The implications of this study can be used in emergency prevention management, especially for road maintenance services, so that they can be on alert or mobilize the necessary resources in advance depending on the intensity of the expected rainfall. In this sense, a graph (Fig. 7) has been prepared for the Anaga Sector, which relates the level of expected rainfall—type of alert with the probability of at least one event occurring on that day. The alert system is similar to the meteorological alert system used by the AEMET (yellow, orange and red levels whose thresholds for Tenerife are 60/100/180 mm in 12 h), with the following results:

- A yellow alert (or pre-alert situation according to the DGSE of the Government of the Canary Islands) indicates the probability of at least one event occurring in the Anaga Sector ranges between 70 and 90%.
- An orange alert indicates a probability ranging between 70 and 90%.
- A red alert indicates a probability of 100%.

### 4 Conclusions

Intense rainfall modifies hydrogeological conditions and water levels. Surface movements, predominantly of soils and altered materials, can be triggered. These movements can include new landslides or debris flows, reactivation of old landslides and rockfalls.

From the analysis of the data, it can be concluded that there is a direct relationship between accumulated rainfall and the occurrence of instabilities. The greatest probability for these events applies to when precipitation is greatest.

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\(^{1}\) http://www.aemet.es/es/portada.

\(^{2}\) http://www.agrocabildo.org/agrometeorologia_estaciones.asp.
This relationship can be used as a predictive tool in emergency management, especially for road maintenance and conservation service. Likewise, it has been possible to verify in a certain Sector that in a relevant percentage, the events do not occur in a rhythmic manner on the same day that the maximum rainfall occurs but until several days later. This circumstance is related to the geomorphology (steep reliefs) and the type of material (strongly altered and weathered on the surface) that makes up the slopes in the Anaga area.

Finally, it should be noted that this study has been based on data provided by the Road Conservation Organic Unit. These data apply only to landslides and rockfalls that occur from slopes adjacent to roads the Unit is responsible for and for events assessed by the Unit. Other events may have occurred in this area but may not have affected a road or may not have been assessed by the Unit. Therefore, the values obtained should be considered as a minimum threshold.

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