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**Deliverable D.E2.4 Hazard map of the Canary Islands
test site.**

A deliverable of
Task E: Geohazard impact assessment

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Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
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EXECUTIVE SUMMARY

SAFETY is a two years research project funded under the ECHO (European Commission's Humanitarian aid and Civil Protection department call "Prevention and preparedness projects in Civil Protection and marine pollution", and it started 1 January 2016. The mission of the project is to improve the efforts in detecting and mapping geohazards (i.e. landslides and subsidence), by assessing their activity and evaluating their impact on built-up areas and infrastructures' networks. SAFETY will enhance ground deformation risk prevention and mitigation efforts in highly vulnerable geographic and geologic regions. The outcomes of the project will provide Civil Protection Authorities (CPA) with the capability of periodically evaluating and assessing the potential impact of geohazards on the selected sites.

D.E2 "Hazard map of the Canary Islands test site" is the deliverable of Task E "Geohazard impact assessment". This deliverable is focused on analyzing rockfall hazard in the Canary Islands test site, this is made through an estimation of the rockfall spatial probability of occurrence, which is used to produce rockfall susceptibility maps for Civil Protection Authorities (CPA).




REFERENCE DOCUMENTS

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1 INTRODUCTION

A procedure to evaluate and assess the potential impact of rockfalls is essential to properly face the risk management of vulnerable areas. In this sense, one of the most important tasks from disaster risk management is to carry out prevention methodologies, products, and services to take actions for the protection of people in case of catastrophes and emergencies. The deliverable D.E2.4 *Hazard map of the Canary Islands test site*, improves the results obtained in Deliverable D.E2.3, designing a methodology capable of generating rockfall hazard maps. Firstly, these maps will identify rockfall prone areas along the GC-200 road (Figure 1), starting from the identification of the sources areas and maps of the dynamic rolling friction coefficient and of the normal and tangential energy restitution coefficients. The final goal is to provide an operable methodology, a protocol, which can be integrated into Civil Protection prevention activities, and providing the capability of evaluating and assessing rockfall hazard. This methodology is based on rockfall simulations, and involves three main phases: (1) inventory, (2) simulation, and (3) validation. This deliverable is one of the deliverables foreseen in Task E: “Geohazard impact assessment” in which the methodology was detailed.



Figure 1: The GC- 200 road between the localities of Agaete and Aldea. It is considered one of the most hazardous roads in Europe. Numerous rockfalls cut the road off every year.

2 ROCKFALL HAZARD ANALYSIS

To generate a rockfall hazard map, we have exploited STONE, a GIS based rockfall simulation software which computes 2D and 3D rockfall trajectories starting from the identification of the sources areas, the digital terrain model (DTM) and the maps of the dynamic rolling friction coefficient and of the normal and tangential energy restitution coefficients. The appropriate identification and definition of these parameters determines the accuracy of the simulation. We have developed a method to calibrate and validate the STONE rockfall modelling software in a volcanic context for the first time, to provide to Civil Protection a reliable tool to assess hazard and risk posed by rockfall at regional scale, which could be applied later in any island of the archipelago.

2.1 Improving the rockfall model

2.1.1 Calibration of input data

According to the field observations and the geological map available -GEODE from IGME (www.igme.es)- lithological units were differentiated and their coefficients were firstly obtained from the literature and then, they were calibrated with some well-known rockfall events occurred in the Canary Islands. In this sense, three cases study of rockfall events in the Canary archipelago, which include a wide variety of outcropping lithologies, were used. The selected rockfalls are well-known, as they took place recently, and a detailed field work was carried out.

Rockfall events were simulated using RocPro3D software which uses GIS technology to produce 3D rockfall trajectories lines, estimating velocity and energy of falling blocks as well as bounce heights, impacts and stopping points. For each rockfall event, according to field observations and the available geological map, some lithological units have been differentiated. Coefficients values have been changed in numerous attempts in order to select those where the extent and shape of the simulation matched the field mapping (the runout distance, the propagation areas, and the location of impacts). Best results were summarized with the average statistical values (mean, median and mode) for each parameter and for each geotechnical unit, and determining that median values represent more precisely the data. The study cases selected were: Risco de Tibataje (El Hierro, 2011), Los Berrazales (Gran Canaria, 2017) and El Rincon cliff (Gran Canaria, 2013).

Risco de Tibataje (El Hierro)

The first case study-took place along the HI-5 road on the island of El Hierro during the 2011 volcanic crisis. In this event, several boulders impacted over the Roquillos tunnel's northern entrance. The identified rockfalls events were dated on February 21, June 23, and June 26. Risco de Tibataje rockfall event was simulated using RocPro3D software (www.geociel.fr). The input digital elevation model was obtained by the National Geographic Institute (www.ign.es) at a 5 m

x 5 m resolution. According to field observations and the available geological map, lithological units were differentiated. Three rockfall source areas were located at the upper part of the Risco de Tibataje cliff based on field observations. These source areas were used to release 250 rock blocks, calculating their energy, velocity, height, density and impact information for every trajectory (Figure 2).

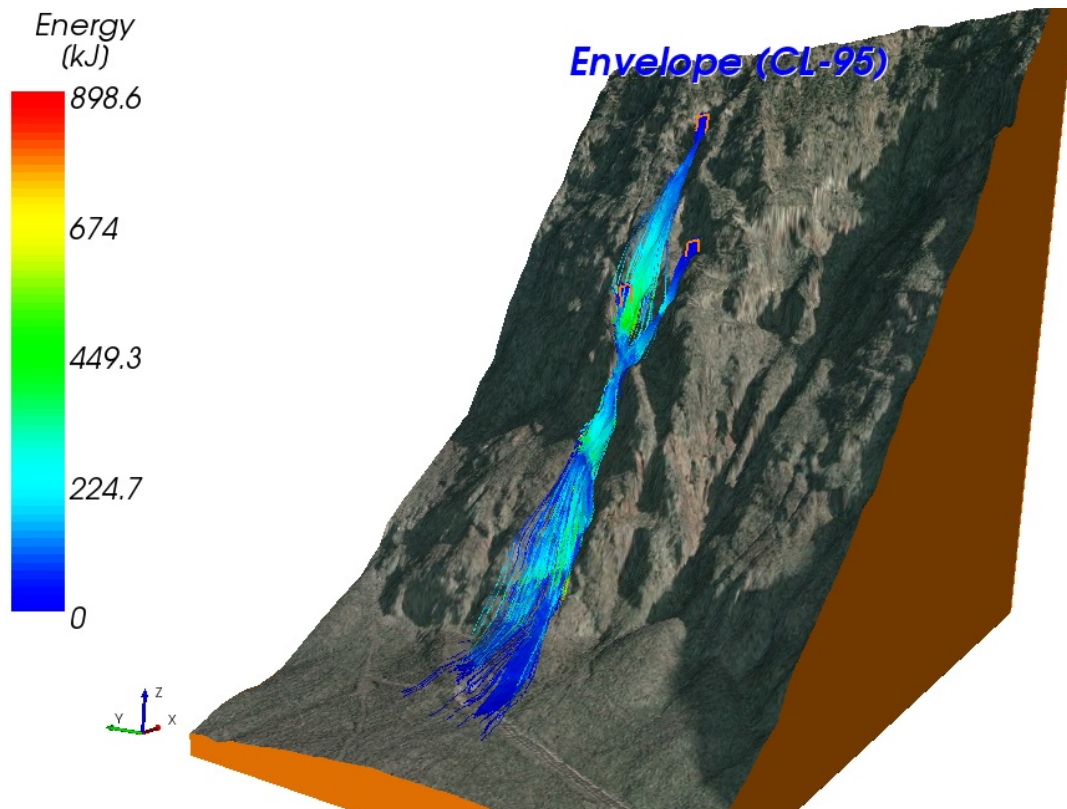


Figure 2: Energy map computed by RocPro3D. Risco de Tibataje (El Hierro)

Los Berrazales (Gran Canaria)

The second case study was located in Los Berrazales (Gran Canaria). On Sunday 12th February 2017, two German visitors were injured after being impacted by a boulder with a volume of 0.25 m³, in the Old Herradura track between Los Berrazales and El Sao. This event was also simulated using RocPro3D software. The input digital elevation model was generated with LIDAR data at a 1 m x 1 m resolution. Due to the vegetation in the area, the source area was located based on the CPA's field work observations (Figure 3).

In this case, two lithological units were differentiated: hard rocks corresponding to basalt formation, domo and road, and moderately hard rocks corresponding to "tobas ignimbríticas".



Figure 3: Field work observations by CPA's in Los Berrazales (Gran Canaria)

El Rincón (Gran Canaria)

The last case was the El Rincon cliff case study, taking into consideration the work carried out by Rodríguez-Peces et al. (2012). Authors analysed the rockfalls triggered along the cliff and their consequences over the GC-2 highway, located at the base of the cliff. This case was also simulated using RocPro3D software (Figure 4).



Figure 4: Simulated trajectories by RocPro3D in El Rincon (Gran Canaria)

To decide the most appropriate values for the parameters for each lithological unit, a statistical analysis was carried out taking into account the three cases of study. Statistical values for rolling friction, normal and tangential restitution parameters, obtained for each geotechnical unit, were selected considering the best attempt for each case study. Median values were selected as the calibrated parameters (Table 1).

HARD ROCK					
	MAX	MIN	MEAN	MODE	MEDIAN
RESTITUTION COEFFICIENTS					
R _n	0.64	0.52	0.58		0.58
R _t	0.88	0.83	0.87	0.88	0.88
FRICITION COEFFICIENT					
k	0.62	0.49	0.53		0.51

Table 1: Results summarized with the average statistical values (mean, mode and median) for hard rock

2.1.2 Expansion of the study area

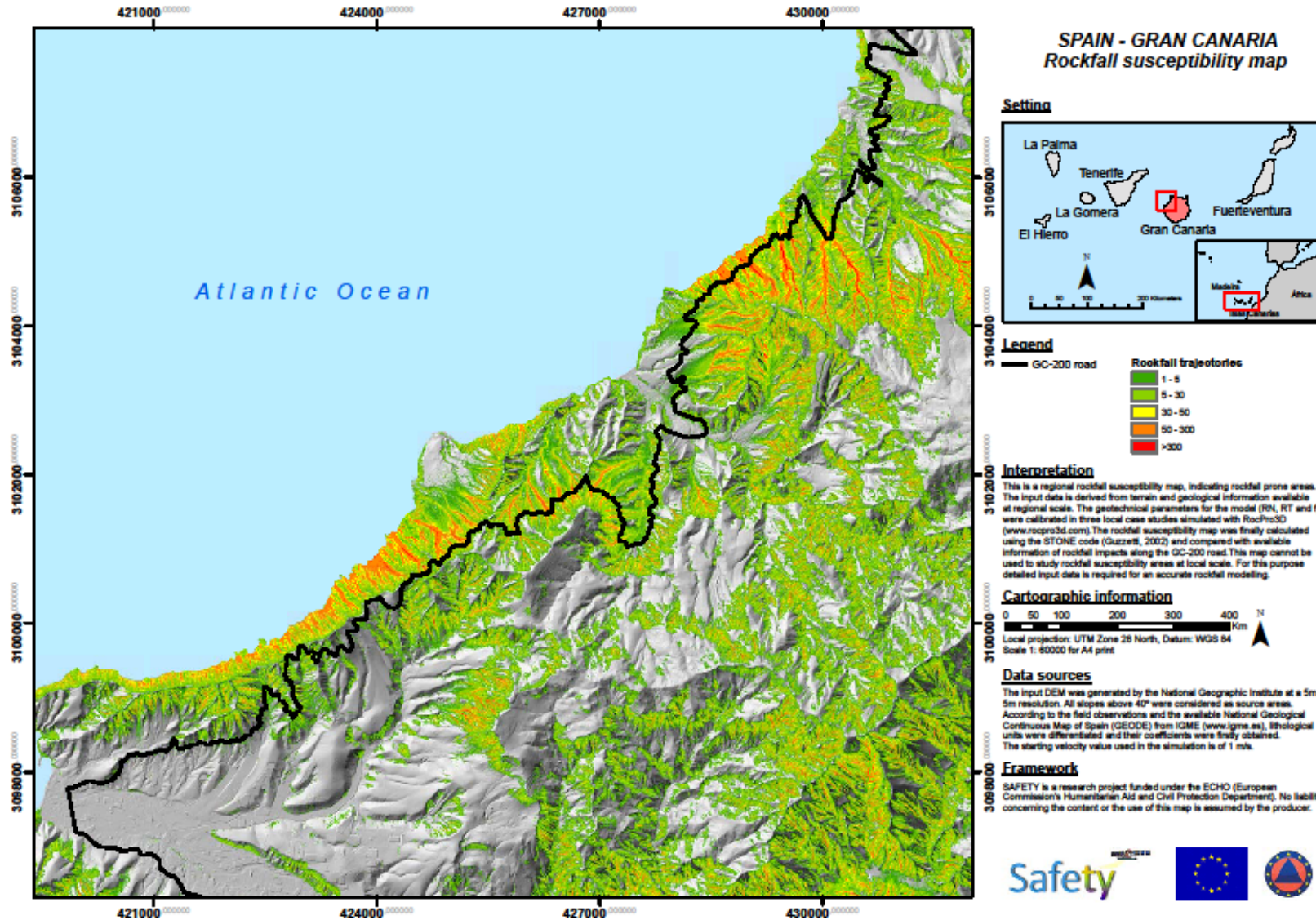
The first section of the road selected in the deliverable D.E2.3 was located in the western extreme of Gran Canaria, and specifically between the localities of Agaete and El Risco. In the deliverable D.E2.4, we widened the study area and the section between El Risco to Aldea (20.2 km) was included. This new section is the most hazardous section, where the largest rockfalls occur, and therefore, dynamic retaining walls and numerous steel wire nettings were installed. Even though, currently, and alternative route (with tunnels) was opened in April 2017. The old section will be of interest only for tourists and for natural/science activities.

2.2 Rockfall simulation

2.2.1 GC-200 road

STONE was the software applied for rockfall simulation along the GC-200 road. STONE differs from other rockfall simulation computer programs in two ways: (a) topography is provided by a DEM and (b) values for the coefficients are provided in a spatially distributed (i.e. geographical) form. The software requires the following input data: the location of the source areas, a digital elevation model (DEM), the starting velocity, and the coefficients of normal and tangential energy restitution and friction to simulate the loss of energy when rolling and at impact points. DEM was generated by the National Geographic Institute at a 5m x 5m resolution (www.ign.es) and included the entire length of the GC-200 road between the localities of Agaete and Aldea. All the cells with slopes above 40° were considered as the sources areas according to several previous studies (Houtian, H., 1989; Look, B. G., 2014). Five boulders for each cell were launched. In addition, we had compared some LiDAR point clouds, taken from different time-periods, to identify the areas with material losses to try to adjust better the source areas. According to the field observations and the geological map available -GEODE from IGME (www.igme.es)- some lithological units were differentiated and their coefficients were obtained from some well-known rockfall events occurred in the Canary Islands. The starting velocity in the preliminary simulation is 1 m/s. The software computes, for each DEM cell, the cumulative count of rockfall trajectories, the maximum computed velocity, and the largest flying height produced.

The map results is a proxy for the probability of occurrence of rockfalls and shows the maximum computed rockfall velocity and the maximum computed flying height, both outputs provide information on the (maximum) expected intensity of a rockfall. For the rockfall simulation carried out along the GC-200, only the rockfall counts map was used and it was developed according to the INSPIRE directive and the requirements of the users.

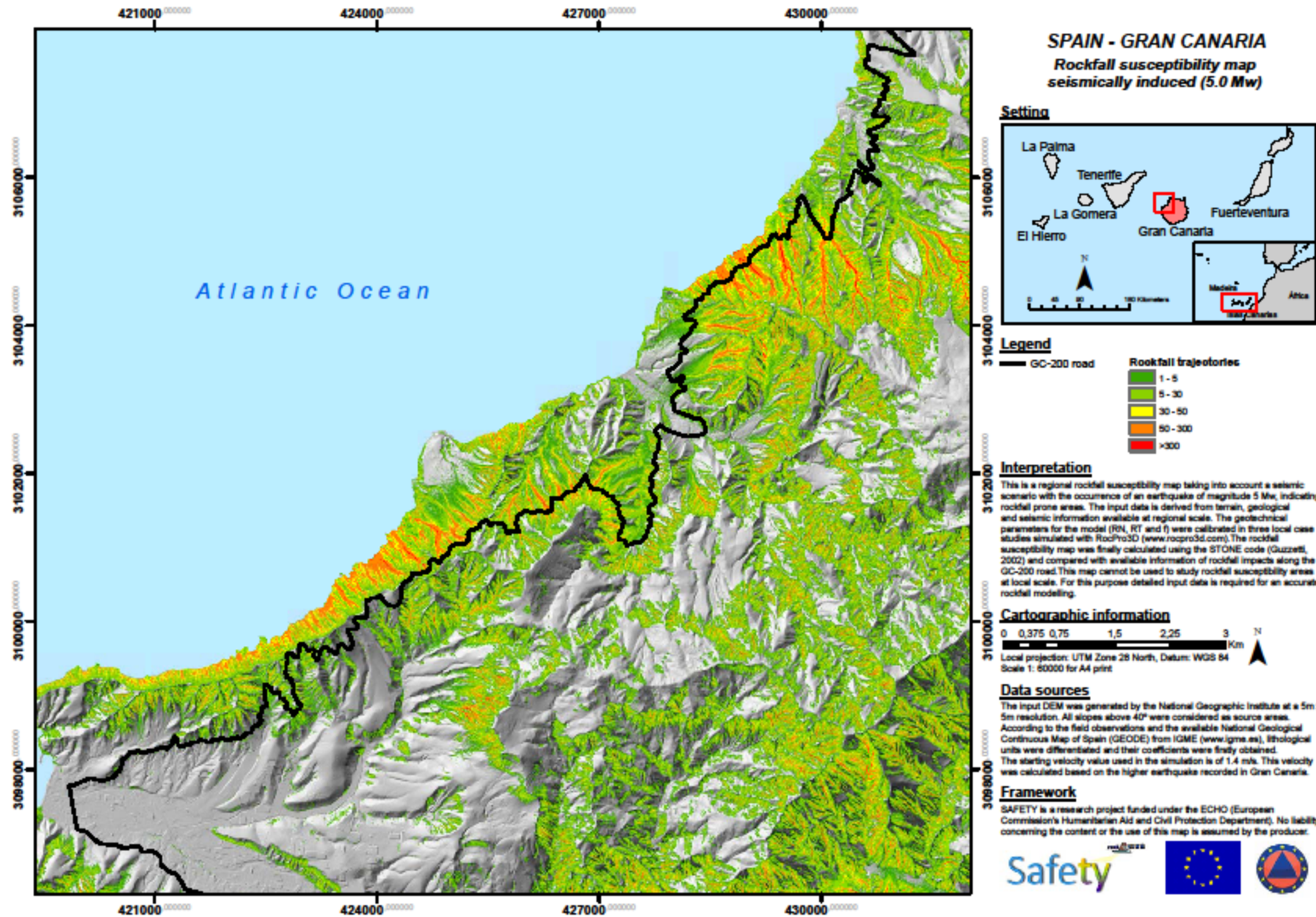


2.2.2 GC-200 road in seismic scenario (5.0 Mw)

A second rockfall simulation was carried out considering a seismic scenario. We exploited the same input data but varying the starting velocity. To calculate the starting velocity we consider the highest magnitude earthquake recorded in a buffer area of 50 km from the centre of Gran Canaria (Table 2). The data acquired were the following: depth (km), intensity, magnitude and location. Data from IGN reveals that the maximum magnitude recently registered was around 5.0 Mw. We used this value to calculate the starting velocity. We applied a seismic analysis (Atkinson (2010); Munson & Thurber (1997) which obtain two ground motion intensity measures: peak ground acceleration (PGA) and peak ground velocity (PGV), and taking into account the topographic amplification factor. According to this, the starting velocity used for the present work is 1.4 m/s. Next figure shows the results of the STONE simulation considering this seismic scenario.

Date	Latitude	Longitude	Depth (Km)	Inten.	Mag.	Type Mag.	Location
24/06/1913	27.9000	-15.5500		VII			INGENIO.GC
16/06/1915	28.3500	-14.1167		VII			PAJARA.FV
20/01/1920	28.7667	-17.8667		VII			MONTAÑA CUMBREVIEJA.LP
09/05/1989	27.9467	-16.2000	36	V	5.2	2	ATLÁNTICO-CANARIAS
27/12/2013	27.7806	-18.2984	12	V	5.1	4	W FRONTERA.IHI

Table 2: Seismic data generated by IGN



3 CONCLUSIONS

This study presents a methodology to provide the Civil Protection Authorities of the Canary Islands the capability of evaluating and assessing rockfall susceptibility. The comparison of the map of the potential rockfall trajectories obtained by STONE with the location of the impact points of the historical rockfalls along the road, exhibits a good correlation. These maps provide the number of trajectories that cross each cell. Maps were elaborated according to the INSPIRE directive and the requirements of the users.

In first section of the road, from Agaete to El Risco (13.380 km), the highest density of trajectories is located (between the PKs 7 and 9), where higher densities of rockfall events were identified. Additionally, between the PKs 9 and 11, higher densities were also observed. In the second section, from El Risco to Aldea (20.2 km), the highest density of trajectories is located in between the PKs 17 and 22. Overall, the numbers of trajectories are in agreement with the information and observations carried out by the Canarian CPAs.

The results permit to conclude that:

1. The rockfall susceptibility map, elaborated with a 5 m x 5 m DEM, is useful to identify rockfall prone areas. These maps cannot be used at local scale, where a detailed Digital Elevation Model (DEM) is required for an accurate rockfall modelling.
2. The source areas, were determined from slopes greater than 40°. However this basic approximation should be improved focusing on a statistical identification of the rockfall source areas.
3. Maps of the dynamic rolling friction coefficient and of the normal and tangential energy restitution coefficients were upgraded and improved. To calibrate them, we have selected 3 well-known rockfalls which include a wide variety of outcropping lithologies. For a better identification of these parameters, new cases should be included.
4. We have calibrated and validated the STONE software for the first time in a volcanic context, developing a reliable tool, which can be applied in any rockfall prone area of the archipelago.
5. Seismic scenarios have been simulated by calculating the starting velocity (1.4 m/s). The volcanic crisis in El Hierro in 2011 showed a seismic scenario with numerous earthquakes over 4.0 Mw.

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