Plan de gestión de carreteras en base a la calibración y validación de un modelo de desprendimientos rocosos. Aplicación en Mallorca

Roadway management plan based on rockfall modelling calibration and validation. Application in Mallorca

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Abstract: The Tramuntana range, in the northwestern sector of the island of Mallorca (Spain), is frequently affected by rockfalls which have caused significant damage, mainly along the road network. In this work we present the procedure we have applied to calibrate and validate rockfall modelling in this region, using 103 cases of the available detailed rockfall inventory. We have exploited STONE (Guzzetti et al. 2002), a rockfall simulation software which computes 2D/3D rockfall trajectories starting from maps of the dynamic rolling friction coefficient and of the normal and tangential energy restitution coefficients. The appropriate identification of these parameters determines the accuracy of the simulation. To calibrate them, we have selected 40 rockfalls along the range which include a wide variety of outcropping lithologies. 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. For the validation stage, confidence tests have been applied to 10 well- known rockfalls triggered during the rainy period 2008-2010. We have further validated the calibrated parameters along the Ma-10 road using the 63 rockfall recorded during the past 18 years along the road. Results have been exploited for the design of the road management plan at short, medium and long term.

Key words: Rockfall, Modelling, Calibration, Validation, Road management, Mallorca

Resumen: *La Serra de Tramuntana de Mallorca se ve afectada con frecuencia por desprendimientos rocosos que causan numerosos daños en la red de carreteras. En el presente trabajo se muestra la metodología llevada a cabo para calibrar y validar un software de modelización de desprendimientos rocosos mediante la utilización de 103 casos del inventario. Se ha utilizado el software denominado STONE (Guzzetti et al., 2002) que simula en 3D/2D las trayectorias de los bloques a partir de una serie de coeficientes que dependen de las características geológicas de la ladera y su topografía. La apropiada determinación de estos parámetros condiciona el éxito de la simulación. Para la calibración se han seleccionado 40 desprendimientos que abarcan una gran variedad de litologías presentes en la Tramuntana. Los coeficientes se han ido fijando a partir de numerosos intentos, seleccionando aquéllos donde la modelización se ajusta muy bien a la realidad. Para la validación, se han llevado a cabo una serie de pruebas que evalúan los éxitos y los errores de la modelización aplicada a 10 desprendimientos bien conocidos, ocurridos durante el lluvioso periodo 2008-2010. Posteriormente, los parámetros ya calibrados se han validado en 63 desprendimientos registrados durante los últimos 18 años en la carretera Ma-10, la principal vía de comunicación de la Serra. Los resultados obtenidos han permitido desarrollar el Plan de gestión de la carretera a corto, medio y largo plazo.*

Palabras clave: *Desprendimientos rocosos, Modelización, Calibración, Validación, Gestión carreteras, Mallorca*

INTRODUCTION

The island of Mallorca has a variety of different geomorphological domains, most prominently the Tramuntana Range (1,100 km^2) in the northwestern part of the island (Fig. 1). The steep topography of the chain, highly related to its geological complexity, influences intense slope dynamics with the consequent multiple types of slope failures (Mateos 2002; Mateos et al. 2007). The northern and coastal face is more hazardous due to the existence of steeper slopes conditioned by the NW-overlapping thrusts and the regional tectonics. The predominance of Jurassic massifs made up of limestone and dolostone and the structural setting justify the frequent rockfalls along the

Tramuntana range. The historical landslide inventory reveals that 70% of the events (630 cases) correspond to rockfalls (Mateos 2006). The rockfall volumes range from 0.1 to 500,000 m^3. Frequency and volume has an inverse relationship. Between 2008 and 2010, the island of Mallorca experienced the coldest and wettest winters of the last 40 years. The severe climate conditions triggered various rockfalls which caused serious circulation problems in the road network of the range (Mateos et al., 2012).

In this paper we present the procedure we have applied to calibrate and validate rockfall modelling in the Tramuntana range using STONE (Guzzetti et al. 2002), a physically-based rockfall simulation computer program which computes 2D and 3D rockfall trajectories and requires, between other inputs, maps of the dynamic rolling friction and of the normal and tangential energy restitution coefficients. Calibration and validation were performed using 103 cases of the rockfall inventory. This study aims to get a reliable tool which contributes to future rockfall hazard and risk evaluation in order to address preventive and corrective measures. In fact, results have been applied by the Road Maintenance Service of Mallorca to design a management plan along the main road of the region (Ma-10).

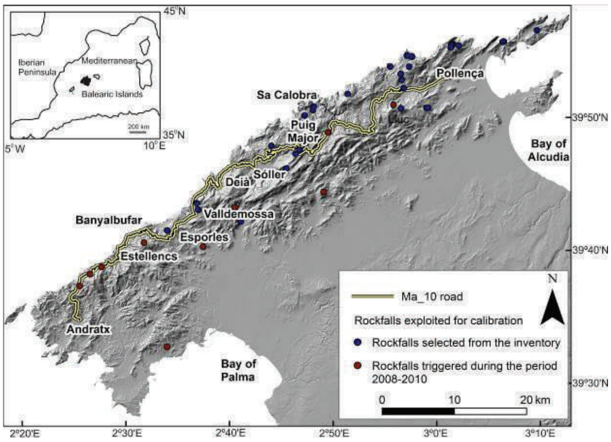

FIGURE 1. Location of the Tramuntana Range on the northwest extreme of Mallorca. The 40 rockfalls exploited for the calibration stage are indicated over a Digital Terrain Model. The 10 rockfalls triggered during the period 2008-2010 are differentiated by red points. The Ma-10 road is also drawn, which is the connecting via for the main municipalities of the range

CALIBRATION

In order to calibrate the friction and energy restitution coefficients, 40 rockfalls along the range, which include a wide variety of outcropping lithologies, have been used (Fig. 1). They have been selected from the inventory taking into account numerous geological and geomorphological criteria. Initially, values of friction, normal and tangential restitution coefficients for running STONE were obtained from the literature (Guzzetti et al. 2003; Guzzetti et al. 2004; Sarro et al. 2014). For each rockfall, the map of the count of rockfall trajectories was compared with the extent of the rockfall deposits mapped in the field (Fig.2).

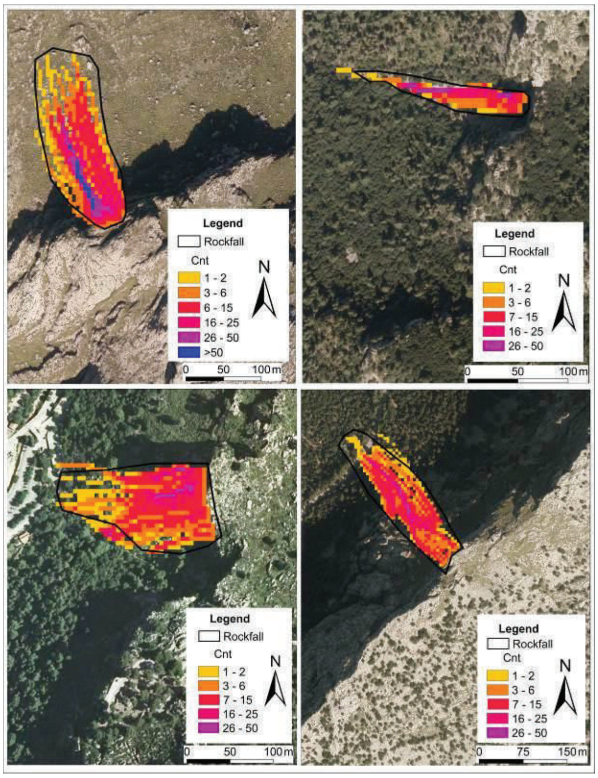

FIGURE 2. Four cases from the 40 used for STONE calibration in the Tramuntana range. Output values correspond to the cumulative count of rockfall trajectories (colors). The real area covered by the rockfall boulders is delimited by the polygon with black boundary. The figures show the best simulation for each case, after numerous attempts.

Geotechnical classification	Rolling	Normal	Tangential
Hard rocks	0.40	65	78
Moderately hard rocks	0.5	58	68
Soft rocks	0.62	59	60
Soft soils	0.59	53	56
Very soft soils	0.61	40	52

TABLE I. Statistical values for rolling friction, normal and tangential restitution parameters obtained for each geotechnical unit, taking into account the best attempt for each rockfall (40 events).

The process was repeated for each case several times, changing the parameters; until the result was judged satisfactory (the extent and shape of the simulation matched the field mapping). Best results were summarized with the average statistical values (mean, median and mode) for each parameter and for each geotechnical unit. Later, a statistical analysis has been carried out to decide the most appropriate average values that will be considered as the calibrated parameters (Table I).

VALIDATION

In order to validate the calibrated parameters, two phases have been performed:

(1) Taking into account the detailed field knowledge for the 10 rockfalls triggered during the period 2008-2018, modelling results have been validated by applying two confidence tests. The first test is based on the comparison between the mapped and the simulated rockfall, analyzing the histograms which show the number of cells falling inside and outside the mapped geometry (Fig.3). The second test is a new approach, which considers not only the number of cells inside the rockfall deposit (success), but also the number of cells inside the real deposit and with no modelling results (failures).

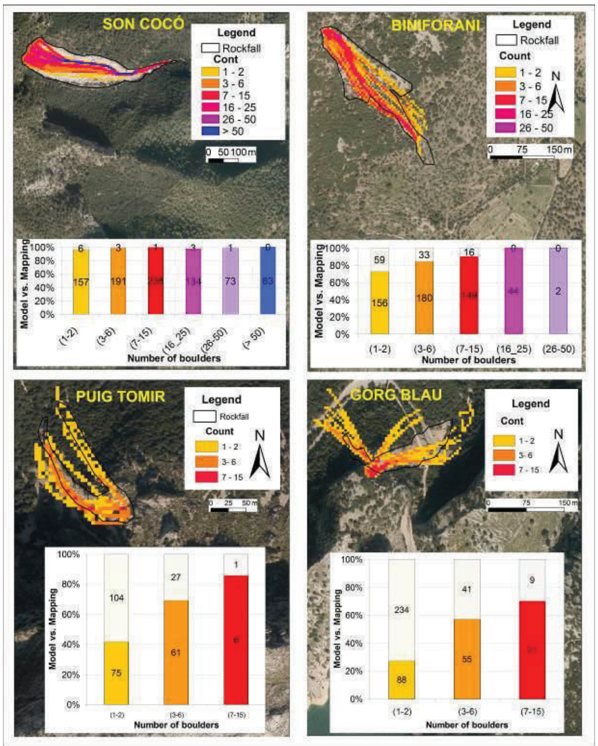

FIGURE 3. Validation test. Comparison between the mapped rockfalls (black polygon) and the simulated rockfalls (colors) in four well-known rockfalls triggered during the period 2008-2010. Histograms show the number of cells falling inside (colored) and outside (white) the mapped rockfall.

(2) Final validation was carried out along the Ma-10 road, where 63 rockfalls have been recorded during the past 18 years. STONE simulations were run with the calibrated parameters considering all possible source areas in both sides of the road. Results were compared with the 63 real cases in order to determine the accuracy of the simulation.

Conclusions were discussed by the technical team from the Road Maintenance Service of Mallorca with the aim to lay down new guidelines for the Ma-10 road prevention and prediction measures.

DISCUSSION AND CONCLUSIONS

Results have been analysed in detail by the technical team from the Road Maintenance Service of Mallorca.

Since 2008 they have changed the road- management policy. Before this time, the Service only focused on repairs and maintenance, with a reduced budget. Since the severe damage caused in the road by the rockfalls registered during the period 2008-2010, when the road was cut off for a long time, they have laid down new guidelines for prevention and prediction measures. From this point of view, they have discussed the results and make the following considerations:

- Modelling rockfalls from road-cuttings is not of interest, as they have well identified the black spots along the road and the investment involved in repairing and maintaining works is very low compared with total amount. In this sense, the low success obtained for this kind of rockfalls is irrelevant.

- Modelling rockfalls with source areas in natural slopes is of interest, as the past events have caused severe damage and the investment involved in repairing and maintaining works has been very high (around 4M Euros). Taking into account the results obtained in the present work, three temporal phases have been established for the management of the road:

(1) Phase 1. Short-term. Design a specific plan for the road- sections where rockfalls were registered and modelling results were obtained. A large investment will be expended for implementation of retention and protection measures.

(2) Phase 2. Medium-term. Design a specific plan for the road- sections where rockfalls were registered but no modelling results were obtained. For these cases, new studies at local scale are necessary as well as the application of other modelling software which include higher resolution input data.

(3) Phase 3. Long-term. Design a specific plan for the road- sections where no rockfalls were registered but modelling results were obtained. These are potential rockfall areas and local and specific ground studies are necessaries.

Road Maintenance Service of Mallorca asserts that a calibrated and validated rockfall modelling provides a useful tool to assess hazard and risk posed by rockfall in the road.

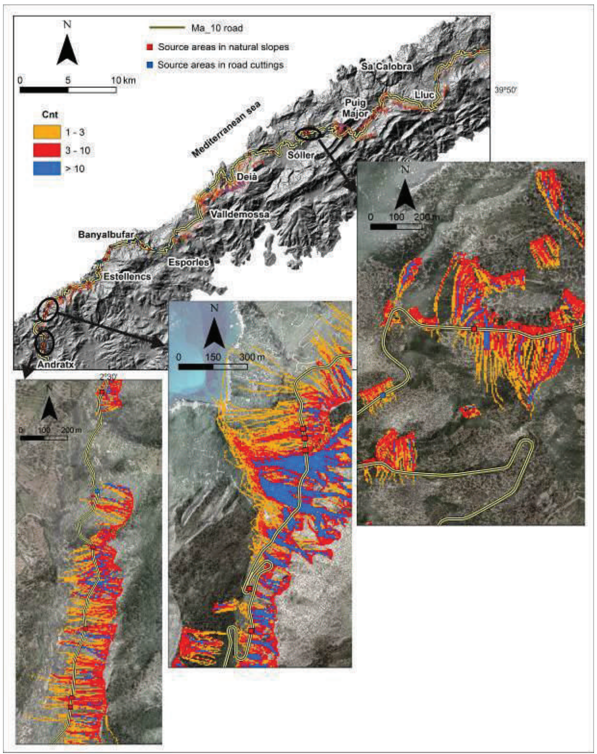

FIGURE 4. STONE results along the Ma-10 road. 81.5% of events are well represented by STONE, as their cells are within the rockfall trajectories. Small sections of the road have been represented where three scenarios can be seen: (1) rockfalls were registered and modelling results are obtained; (2) rockfalls were registered but no modelling results are obtained, and (3) no rockfalls were registered but modelling results are obtained.

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