The Formentor rockfall in Mallorca (Spain): new protection barriers

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Abstract

The Formentor peninsula, located in the northern part of Tramuntana mountain range in Mallorca (figure 1), is a very prone area to rockfall events, as the whole range, due to its geological characteristics, with alternative presence of weak rocks and hard but fractured rocks, in addition to its typical Mediterranean climate with high intensity rainfall events. The main road of Formentor, Ma-2210, has been systematically affected by rockfall events and, hence, different rockfall protection systems were installed more than 25 years ago. The specially wet winter of 2017 affected several areas all over Tramuntana range with rockfall events of different magnitudes up to hundreds of cubic meters mobilized damaging roads and some of their facilities. The rockfall event of January 30th, 2017, mobilizing about 14 m^3 *of rock blocks, affected an area where the Formentor road crosses a specially threatened cliff and talus slope area, severely damaging the installed dynamic barriers requiring their replacement. The protection energy of the existing barriers had been exceeded. Therefore, a new stability analysis with rockfall simulation was performed. An updating of the design parameters of protection systems was also undertaken in compliance with European Standards. Previous tasks including field investigations of rockfall event conditions such as geological characteristics of detaching area, rock mass joint sets, rock volumes mobilized, their trajectory, run-out, impacts on the ground and fragmentation of rock blocks were also carried out. Impact energy and rock block fragmentation models were applied for the first time in the Tramuntana range to determine actual design parameters for an update of rockfall protection systems. Even with the application of such models, an increase of protection energy and height of barriers was needed although up to reasonable values of 3,000 kJ and 4m height. Finally, an emergency executive project to replace damaged dynamic barriers was developed and they were installed by the end of April 2017.*

Figure 1. Location of Tramuntana Range in the northwest side of the island of Mallorca in the western Mediterranean Sea and the Formentor rockfall of January 30th 2017. Other rockfall events of winter 2017 are also located

1 INTRODUCTION

The main mountain range of Mallorca island (Balearic Islands), Serra de Tramuntana, is located in the north-western side of the island in the western Mediterranean Sea. In this mountain area, a transportation net of roads of about 400 km communicates the villages and houses of Tramuntana area. The Council of Mallorca (CIM) is the local authority that owns the island's net of roads and is in charge of developing the net and its maintenance. It also must protect the roads' users and is the responsible of risk mitigation. Since the range is a very prone area to rockfall due to its geological characteristics in addition to its typical Mediterranean climate with high intensity rainfall events (Mateos et al. 2012), risk assessment and mitigation tasks have been undertaken by local authorities last years in an attempt to improve security of such installations. Some protective measures, like dynamic barriers and other structures like wire meshes (simple and double twisted hexagonal) and steel cables nets, have been implemented in recent years (Rius et al. 2016).

From a geological point of view, Tramuntana ranges parallel to the coast with SW to NE direction and it has an abrupt area of superimposed folds of Jurassic and Cretaceous ages, compounded by dolomites, marls and limestones sliding upon Triassic materials, and it is also compounded by conglomerates, detritic limestones, marls and clays of Miocene age. It has a very complex geological structure, with several longitudinal and traverse faults and thrusts (Gelabert et al. 1992). The outcropping materials are of different typologies, the most frequent ones are competent Liassic limestones and dolostones, Raethian marly limestones and poor shales and gypsum of Keuper age. There are several cliffs and escarpments in the limestones and their weathering and fracture conditions make them a very prone area of rockfall events. The rockfall volumes involved ranges from some little rock blocks to thousands of cubic meters of blocks. The dimensions of cliffs, escarpments and hill-slopes up to hundreds of meters high with a large run-out area down-slope and volumes involved threaten structures like roads, houses or any installation and their users.

During the winter 2017 a new short but specially wet period triggered several rockfall events, some of them damaging Tramuntana roads. One of them affected the road of Formentor peninsula near Pollença village. It has been a systematically affected area by rockfall events and different rockfall protection systems were installed more than 20 years ago, the first rockfall protection installed on the island (Rius & Aguiló 2017). The relative big magnitude of the 2017 event caused the toppling of a section of the installed dynamic barriers. An emergency action had to be undertaken to restore the security of the road, with the replacement of the barriers. A previous question about effectiveness of existing rockfall protection barriers arose and, therefore, previous tasks had to be undertaken to consider actual rockfall event conditions.

In this paper, the tasks performed to take into account such special event conditions about rainfall as triggering factor and the geological characteristics of the site for a new design of rockfall protection barriers to consider both magnitude of the event and compliance with European Standards are explained. Previous field investigations of rockfall event conditions such as geological characteristics of detaching area, rock mass joint sets, rock volumes mobilized, their trajectory, run-out, impacts on the ground and fragmentation of rock blocks were also carried out. After field investigations, stability analyses were performed with the simulation of the rockfall event and for dimensioning purposes with rock volumes determined. Impact energy and rock block fragmentation models were also applied for the first time in the Tramuntana range to determine actual dimensioning parameters for a new design of rockfall protection systems.

2 THE FORMENTOR ROCKFALL ON JANUARY 30TH, 2017

The wet period of winter 2017 during December 2016 and January 2017 triggered several rockfall events with different rock volumes involved: January 20th at Coll de Sóller, 160 m3; January 25th at Estellencs, 20 m^3; January the 30th at Formentor, 14 m^3 and other minor events (figure 1). All along the range rockfall events occurred and different incidents affecting main roads took place. All events triggered at the end of January 2017 were strongly related to rainfall. This relationship between rainfall and rockfall activity in Tramuntana range has been previously estudied with ancient rainfall events (Mateos et al. 2012), and maximum of cumulated rainfall and previous daily rainfall were reported as triggering factors.

On the evening of January 30th, 2017, the presence of rock blocks on the road that prevented circulation was reported by CIM road maintenance service due to a rockfall at km 6.2 of Ma-2210 road. They were able to restore circulation as only partial blockage of the road occurred. Afterwards, it was found that the detachment had affected a certain long of the dynamic barriers that were protecting the area of Mal Pas (Formentor). A rock mass of about 14 m^3 was detached from a cliff about 45 m far from the road, moved down the slope and hit an area already protected with dynamic barriers (more than 20 years old and the first installed on the island) knocking them down along a section of 30 m wide and reaching the road (figure 2). Thus, a mass of about a total volume of almost 14 m^3 in several blocks reached the surroundings of the road, having overcome the dynamic barrier being totally inclined, folded supports and lying on the ground. From recent preliminary CIM internal reports, it is interpreted a very low residual resistance capacity, due to damage in most elements, (brakes, ropes, wire nets, rock bolts) although the mass released and their probable impact energy would have overcome their theoretical capacity (1000 kJ and 3 m height) anyway (Rius & Aguiló 2017).

Therefore, it was essential to undertake an emergency action to recover the functionality of the barriers and the security of the road replacing the damaged barriers. A previous question about effectiveness of existing rockfall protection barriers arose. Recent studies show a reduction in residual capacity of barriers after previous impacts (Govoni et al. 2016) and the influence of different design parameters on their effectiveness.

Figure 2. Pictures of Formentor rockfall event with severely damaged lying dynamic barrier and stopped rock blocks close to the Ma-2210 road.

3 ROCKFALL ANALYSES

The question about the functionality requirement of the barriers (in terms of protection energy and height) was raised in the very immediate hours and days after the event. Therefore, it was proposed to perform a new rockfall risk analysis of the affected slope for the assessment of new requirements of the barriers. Different actions were undertaken to achieve this objective:

- Collection of existing data from previous events.
- Inspection of existing barriers, both functional and destroyed sections.
- Field investigations and analysis of collected data, from detached and mobilized mass, from main scar of the actual rockfall event, from other scars on the cliffs and from scatter and cumulated rock blocks on the slope area.
- Development of a new digital terrain model to perform a rockfall analysis, performed by means of an aerial photogrammetric drone flight carried out just after the event.
- Stability analyses by means of application of rockfall simulation models for determination of new requirement parameters and new design of protection measures.
- Execution of projected measures by means of an emergency action.

3.1 Previous history events

Not much previous data of events that have taken place in this area were available. Several rockfall events occurred in early nineties and in January 1994 an executive project was developed to install 3 m height dynamic barrier with low protection energy (150 kJ). In December 1995 a rockfall event overcome the installed barrier and impacted on the road. Several blocks had been retained during 2 years from installation. An additional action was undertaken to update the protection energy of the barrier to a value of 1,000 kJ but no certification report was found. During more than 20 years a lot of blocks have impacted on the barriers, but they been retained (maximum measured retained block volume of 0.8 m^3) until January 30th, 2017 with a 14 m^3 volume rockfall event with several blocks and a maximum block volume of 3 m^3 that overcome the barrier.

3.2 Field data

An on-site investigation was carried out to obtain data from other previous events with blocks that were scattered along talus slope or other stopped blocks by the ancient barrier. Both data from this investigation and geological setting are depicted in figure 3. A drone flight was carried out just after the event to acquire front and overhead image information and photogrammetric data of the whole area to develop a new digital elevation.

The inspection of the ancient barriers had two main sections: the destroyed section of 30 m long and the survival one of 160 m long. Actually, in September 2016 an inspection of existing barriers in the roads of Tramuntana was carried out and a deficient maintenance status in this area (supports, anchorages, brakes, bolts and meshes) was internally reported in CIM. Also, some areas of block accumulation were detected. The destroyed section of the barriers was also analyzed, and it was detected a total section of 30 m and 4 supports pulled out. The whole rock mass that overcome the barriers (figure 4) was about 12 m^3 in several blocks with a maximum block volume of 3 m^3.

An additional investigation was performed to acquire more information about detaching mass conditions in rock cliff. It was an inspection of the cliff from which rock blocks were detaching as an important aspect to be considered like rock mass conditions, rock faults, rock planes and their continuity, persistency or distance, and other ancient detachment areas where other rockfall events have been triggered (Corominas et al. 2017). Several ancient scars and the actual one are depicted in figure 5.

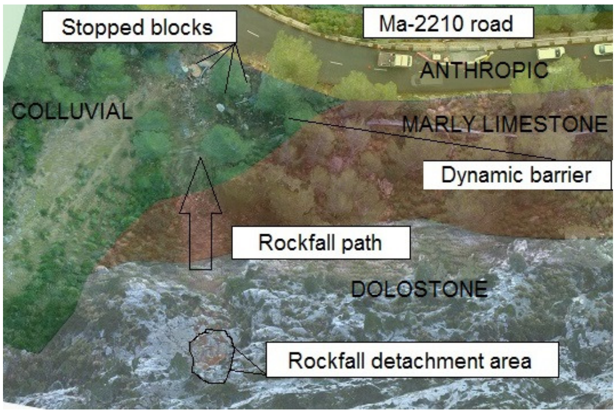

Figure 3. Geological and digital image map with the location of Formentor rockfall area close to Ma-2210 road

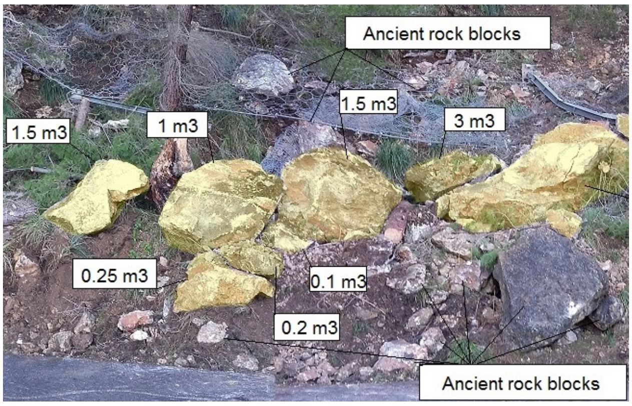

Figure 4. Block volume determination of stopped blocks (yellow coloured) of Formentor rockfall close to the Ma-2210 road area

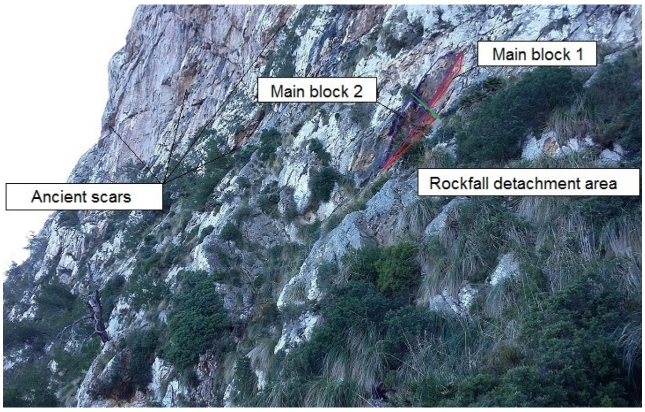

Figure 5. Formentor rockfall cliff area, January 30th rockfall detachment area and other ancient scars. The on-site joint set determination of detached rock blocks was: P1 (340º/42º), P2 (220º/60º) and P3 (160º/50º) metric spacing

From this investigation it was detected that the whole detached mass of the event was about 14 m3 from a height of 15 m from the base of the cliff and 45 m far from de road. This is the considered run-out distance. Rock joint sets (discontinuity planes) were measured: a basal one from which the detached mass slid, and two other discontinuity planes that confine and isolate the blocks. These planes and their spatial configuration, with more than metric spacing, indicated that the detached mass was compound of several initial blocks: at least two big blocks of about 7 and 5 m^3 and some other ones of less than 1 m^3 volumes.

3.3 Analysis of rockfall data

A comparison between detached mass and stopped mass close to the road area was done and important rockfall characteristics could be established, such as fragmentation of rock mass and lost of mass during mobilization. Therefore, they had to be considered during modelling (Corominas et al. 2017). Since block size distribution is considered a key aspect for rockfall risk assessment different patterns about magnitude-frequency of rockfall events have been extensively analysed with different techniques. Thus, the analysis of the Formentor rockfall event was performed taking into account rock fragmentation and impact kinetic energy from collected data. Figure 6 depicts the block size distribution and the adjustment with a fractal fragmentation model. A quite good fit with a power law with an exponent of 0.54 was achieved, value among referenced ones in this kind of events (Matas et al. 2017).

To analyse the energy involved of the event some previous data must be taken into account: height of free fall and impact angle of blocks and type of surface (Giacomini et al. 2009), (Gili et al. 2016). From the locations of the detachment area and the impact area and the inclination angles planes of the in-situ rock masses (figure 7) an approximation of the trajectory of the detached mass has been interpreted. A free height of about 12 m and a displacement of 8 m from the cliff of the detached mass indicates a first impact energy of 2800 kJ for the 7 m^3 block and 2000 kJ for the 5m3 block. The impact angle of about 36º to the impacting plane (dip 29º) has also been interpreted from a parabolic fall with a starting angle of 42º (dip of basal plane), enough for fragmentation of rock blocks.

The main conclusion of the performed analyses is that fragmentation of blocks plays a main role in this cliff area. The detachment area for this event is very close to the impact area (soft rock and talus area), i.e. 12 m of a total cliff height of about 100 m, and most of the rockfall events have taken place from higher detachment areas. Thus, higher values of impact energy and higher impact angles are expected since free fall is longer for most of rockfall events. Therefore, more fragmentation of rock mass is expected from events detaching from higher cliff sites and, in consequence, minor block volumes reaching road area (and protecting measures) are expected. Maximum detachment block volumes expected are about 5 to 10 m^3, although total event volumes could reach similar magnitudes up to 20 m^3 in some very low probability events. The evidences of block dimensions located on talus slopes (one block of less than 5 m^3 and some others less than 1 m^3) and blocks stopped in the barriers in the last 22 years confirm this conclusion.

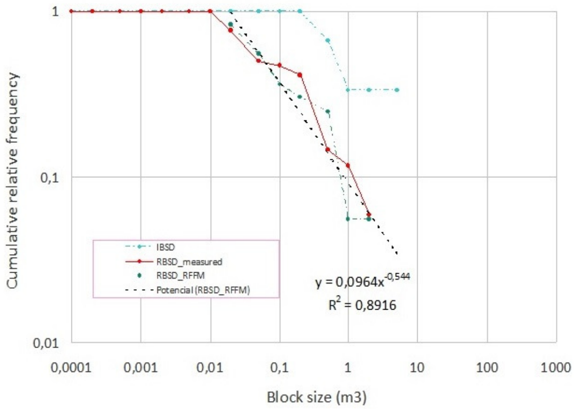

Figure 6. Formentor rockfall different cumulative relative frequency vs block size volume relation-ships: in-situ (cliff) block size distribution (IBSD), ground measured (RBSD_measured), fractal model (RBSD_RFFM) and power-law adjustment (Potencial)

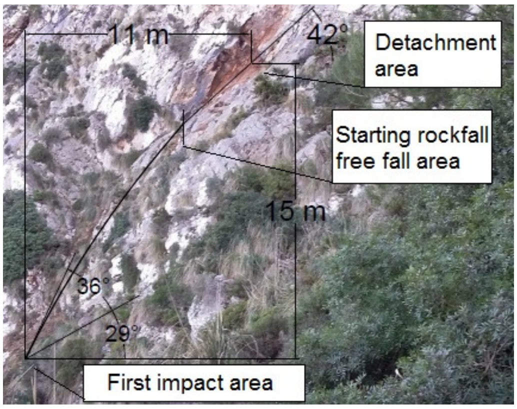

Figure 7. Rockfall trajectory from cliff detachment area to first impact area

4 ROCKFALL PROTECTION SYSTEM DESIGN

4.1 Considered scenarios

The inspection of the mass of blocks that reached the barrier and the data of blocks previously stopped, confirmed another important conclusion. The whole mass that reached the barriers and overcome them (figure 4), about 14 m^3 in several blocks with a maximum block volume of 3 m^3, was the only event of such magnitude that had taken place in the last 22 years in this area. Therefore, as a relatively not frequent event, two main different scenarios were chosen to perform modelling for dimensioning of protection systems purposes: Maximum Energy Level (MEL) and Service Energy Level (SEL) considering European standards of ETAG 027 (EOTA 2008).

The first scenario was a rockfall from the lower part of the cliff (10 to 20 m height) with a maximum rock volume of 4.7 m^3 with ellipsoidal shape taken from on-site investigation (figure 5) as dimensioning of MEL with low occurrence probability. This scenario also included rock volumes of 0.5 m^3 from higher parts of the cliff that hardy fragmented. The second scenario was more likely to occur, and it was a rockfall from all over the cliff with a maximum volume of 0.18 m^3 with spherical shape as dimensioning of SEL. This scenario also included higher volume rockfalls from lower cliff areas that were likely to be fragmented into volumes up to 0.8 m^3, since impact on ground (first impact) of higher volumes are prone to fragmentation.

4.2 Rockfall simulation

The relative uniform morphology had shown a good agreement with a two-dimensional analysis. Different cross sections have been analyzed from available digital elevation model to take into account the worst ones in terms of velocities, energies and rebound height of blocks that reach the road area (figure 8) by means of the Colorado Rockfall Simulation Program v 4.0 (Jones, C.L. et al 2000). The main input parameter values have been selected and adapted from previous references of modelling approaches in Tramuntana range (Mateos et al. 2016). Four main lithological units have been identified (figure 3): Liassic dolostones (hard rocks, cliffs), Raethian marly limestones (soft rocks), colluvial deposits (soft soils, talus slopes) and anthropic coverage (hard soil, roads). Table 1 shows the main parameter values utilized in modelling tasks. Two of the sections have been selected to be representative for dimensioning purposes: cross section 1 from the western part of the cliff and cross section 2 from the eastern part of the cliff (figure 8).

Table 1 Parameter values of main lithological units modelled adapted data from (Mateos et al. 2016)

Parameter	Liassic	Raethian	Talus	Anthropic
Surface roughness (m)	0.5	0.25	1	0.1
Tangent coefficient	0.8	0.7	0.6	0.8
Normal coefficient	0.35	0.25	0.2	0.6

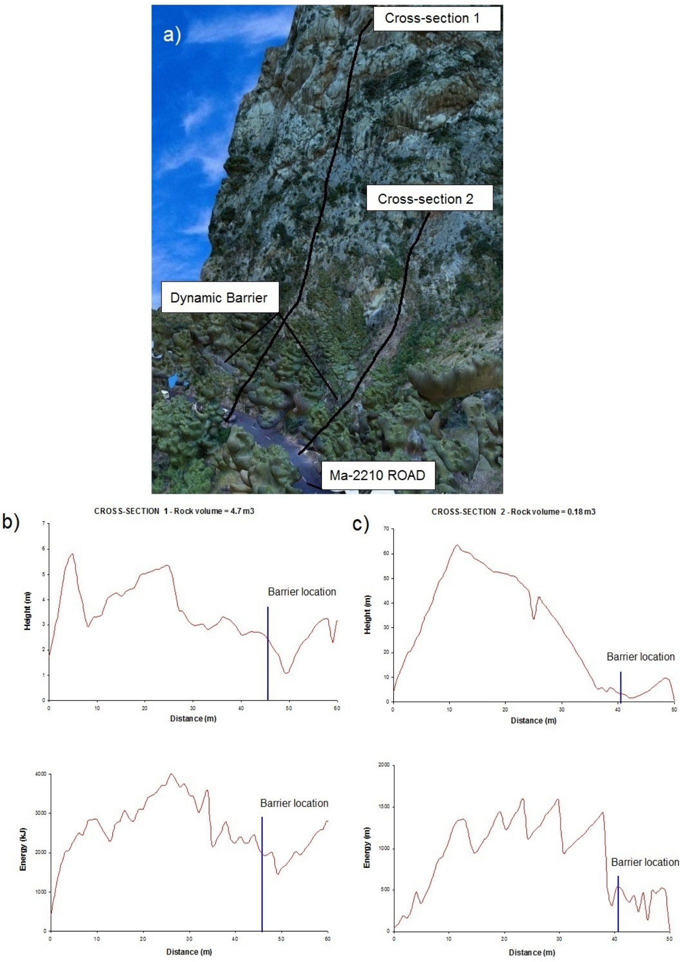

Figure 8. Simulation data: a) two cross-sections considered, b) cross-section 1 (MEL) energies and heights, and c) cross-section 2 (SEL) energies and heights

The computed trajectories analysed have evidenced the under-estimation of height and protection energy of the destroyed dynamic barriers, since in the two different scenarios some design parameters were not enough. Table 2 shows dimensioning values from simulation program modelling performed. Statistical values have been obtained from simulation program in compliance with ONR24810 (Austrian Standard Institute 2013): percentile 99 to consider maximum protection energy of the barriers and percentile 95 to consider maximum height of the barriers. Maximum values of 2250 kJ of calculated energies and 3.2 m of rebound heights reaching the location of existing barriers have been obtained for different scenarios.

Table 2 Dimension values from CRSP. 99% energy and 95% height values taken from simulation program at the location of the destroyed barriers

Scenario	Cross section	Block type	Volume (m^3)	Energy (kJ)	Height (m)
MEL	1	Cylindric.	4.7	2250	2.8
MEL	2	Spherical	0.5	1470	3
SEL	1	Cylindric.	0.8	445	2.5
SEL	2	Spherical	0.18	515	3.2

4.3 Rockfall protection barriers design

The final design of new rockfall protection system has also been performed in compliance with ONR28410 Standard. It accounts for various aspects like damage classification, event frequency and different safety factors may be selected for considered scenarios: MEL or SEL in addition to ETAG027. Therefore, for damage classification, CC2 (medium consequence for loss of human life or economic, social or environmental consequences considerable, secondary roads) was selected. For event frequency, EF2 (1event/year – 1event/30years). Thus, safety factors (SF) for CC2 conditions of 1.05 for barriers protection energy and 1.1 for height of barriers were chosen. The main specific design parameters are displayed in table 3.

The results of the performed analysis led to a new dimensioning for dynamic barriers with a protection capacity to be installed of 3000kJ capacity and 4m height as upper boundary design values. Therefore, in compliance with ETAG027 a barrier with MEL of 3000 kJ and SEL of 1000 kJ was selected. Reduced values of MEL and SEL energies after considering safety factor validate this design in terms of energy and height. Therefore, a uniform value of rockfall protection energy of MEL 3000 kJ (SEL 1000 kJ) and 4 m height was designed. Moreover, as it was detected after field investigations, the west side of the cliff area was not completely protected by existing barriers and in this side the length of protected area was stretched with 30 m of additional protection barrier to a rock wall, with a total length of 220 m. After an emergency project undertaken, in late April 2017 the new dynamic barriers were installed (figure 9).

Table 3. Design values from ONR28410 for dynamic barriers at the location of the destroyed barriers

Scenario	Detachment area	Design energy (kJ)	Design height (m)
MEL	Lower	2363	3.1
MEL	Middle - upper	1544	3.3
SEL	Lower	468	2.8
SEL	Middle - upper	541	3.6

Figure 9. New dynamic barrier on Formentor rockfall area (April 2017 image)

5 CONCLUSIONS

The Formentor rockfall occurred on January 30th, 2017 and affected the Ma-2210 road in the Tramuntana range of Mallorca due to overcome and severely damaging and lying of existing dynamic rockfall protection barriers. Rockfall activity in Tramuntana range is closely related to rainfall events because of its typical Mediterranean climate with high intensity rainfall events along with its geological characteristics that conform several cliff areas prone to detachment of rock masses and rockfall events. In the case of the winter 2017 event, a value of more than 50 mm of daily rainfall in the previous days of the rockfall with a total amount of more than 375 mm of cumulated rainfall within the previous 40 days must be considered as combined triggering factors for this rockfall event.

Thus, a mass of about a total volume of 14 m^3 in several blocks reached the surroundings of the road. The field work carried out by means of aerial and in-situ investigations allowed to identify the detachment area, the aerial and ground trajectory of the main rock blocks to the stop area with a run-out distance of 45 m. Other ancient rock blocks stopped on the existing barriers were also analyzed. This analysis and the detachment area scars allowed the characterization of the event and its relationship with the cliff area in terms of impact energy, frequency and volumes of rockfalls involved.

A rockfall modelling simulation including fragmentation model was also performed taking into account the in-situ data analysis and previous existing data of the main geological characteristics of the range and materials involved. Two different scenarios have been selected to model rockfall events for dimensioning purposes: bigger rock volumes (0.5 – 4.7 m^3) for MEL design with low probability of occurrence and smaller rock volumes (0.18 – 0.8 m^3) for SEL design due to greater rock fragmentation (greater impact energy) and more likely to occur. Therefore, maximum values of 2250 kJ of calculated energies and 3.2 m of rebound heights reaching the location of existing barriers have been obtained for different cross-sections analysed.

The final design of new rockfall protection system has been performed considering ONR28410 and European ETAG027 standards. Energy design values obtained were 3000 kJ for MEL and 1000 kJ for SEL. Reduced values of MEL and SEL energies after applying ONR24810 SF factor validate this design in terms of energy and height. Therefore, a uniform value of rockfall protection energy of MEL 3000 kJ (SEL 1000 kJ) and 4 m height was designed. After an emergency project undertaken, in late April 2017 the new dynamic barriers were installed.

Impact energy and rock block fragmentation models have been applied for the first time in Tramuntana range to determine actual dimensioning parameters for the design of new rockfall protection dynamic barriers. Future work is the extension of the models to other rockfall areas and to update existing rockfall protection barriers.

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