Field trip
Rockfall risk management in the Montserrat Massif

24 May 2017, Montserrat Mountain (Barcelona)
ROCEXS 2017 FIELD TRIP:
ROCKFALL RISK MANAGEMENT
IN THE MONTSERRAT MASSIF

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Xabier Blanch³, David Pare³, Anna Ferré⁵, Pere Buxó⁴

This field trip has been devised as the closure of this sixth edition of the RoceExs workshop,
on the Wednesday May 24th. According to the purposes of this interdisciplinary meeting, most
of the suggested topics for the workshop are tried to be present during the field trip: Rockfall
characterization, inventory and mapping; testing and modeling; hazard and risk analyses;
monitoring; large rockfall cases; protective measures; risk mitigation and management.

We hope that you will enjoy this trip, both from technical point of view and leisure, because
Montserrat Mountain is a special place where earth and heaven meet configuring captivating
scenery. The rockfall risk in Montserrat must be managed properly in order to keep on enjoy-
ing this cultural and natural heritage.

Keywords: risk mitigation, monitoring, hazard analysis, rockfall protection

INTRODUCTION

The technical contents of this field trip are mainly related to the geological risk mitigation
plan in Montserrat (PMRG) that is funded by the Catalan Government, promoted by the
Board of Montserrat Mountain (Patronat de la Muntanya de Montserrat, PMM) and managed
by the Geographical and Geological Survey of Catalonia (Institut Cartogràfic i Geològic de
Catalunya, ICGC). There are also many works done in rockfall protection for the rack railway
by the Railway Catalan Agency (Ferrocarrils de la Generalitat de Catalunya, FGC).

This guide consists on the collection of all the posters that have been used to illustrate the
explanations on the field by the lecturers. They are attached following this abstract. For more
details on each issue, this abstract contains a large list of references of published and academ-
ic works centered in Montserrat and the rockfall risk.

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FIELD TRIP CONTENTS

During the first stop at the rack railway station in Monistrol Vila, a village at the bottom of the mountain, the geological context is presented. From this place we have a nice point of view of the massif, crowned by the Cavall Bernat tower and the Aeri wall, which are emblematic rock faces for climbers coming from all around the world. The ascent to the Sanctuary area is done by rack railway, and just before, it is shortly presented the intense risk mitigation work carried out since its beginning in 2003.

The second stop is placed on the terraces of the upper railway station and Santa Cova funicular that are faced to the Sanctuary and Monastery scenery. The ongoing mitigation plan (PMRGM) for this buildings area and its access infrastructures is exposed. The monitoring works take a relevant role according to the risk configuration, derived from the hazard characteristics, high level of exposure and vulnerability of the 2.5 million visitors that yearly reach this touristic spot of first order.
After a coffee break, the next stop is placed at the entrance of the parking area. Here, the Degotalls wall with several recent rockfalls revealed the critical section of the terrestrial accessibility, because both road and railway are simultaneously exposed to the same hazard focuses. Since these events, new knowledge was born about the precursory signs before the detachment of large blocks. At this stop the main monitoring experiences with remote sensing techniques and its results are presented.

The visit also includes free time for a short visit to the Sanctuary before lunch and later for a light walk in the Natural Park. It is just a taste of the natural and cultural assets that are treasured within the Montserrat Mountain.
CONCLUSIONS

After its first phase during 2014-16 consisting on pilot tests, strategy design and first priorities in protective works, the mitigation plan in Montserrat (PMRGM) carries on with the second phase. From now on, this strategy for the rockfall risk mitigation must be deeply developed and expanded. We hope to be able to report new interesting results from our rockfall research in Montserrat at the next RocExs event, expected for 2020. See you soon, and keep in contact!

ACKNOWLEDGMENTS

The organizing committee wants to acknowledge all the colleagues that have contributed to the field trip organization and guidance. Likewise, we want to highlight the gratitude to the partners that have contributed to make possible this field trip: the Board of Montserrat Mountain (Patronat de la Muntanya de Montserrat, PMM), the Railway Catalan Agency (Ferrocarrils de la Generalitat de Catalunya, FGC) and the touristic and security responsible services of the Sanctuary and Monastery.

REFERENCES


ICGC (2011) Olesa de Montserrat – 392-1-2 (71-30). GeoTreball IV – Mapa per a la Prevenció dels Riscos Geològics de Catalunya 1:25,000

ICGC (2012) Monistrol de Montserrat – 392-1-1 (71-29). GeoTreball IV – Mapa per a la Prevenció dels Riscos Geològics de Catalunya 1:25,000


JANERAS M (2017) ¿Qué nos enseña la pared de Degotalls en Montserrat sobre los desprendimientos de roca? IX Simposio Nacional sobre Taludes y Laderas Inestables, Santander, in press.


OMS O, BIOSA J. La Muntanya de Sal de Cardona i la vall del Cardener. Geocamp (web resource by UAB, UdG, UPC).


Rockfall risk management in the Montserrat massif

Presentation
Location and field trip planning

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**Timetable**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:15</td>
<td>Meeting in UPC</td>
</tr>
<tr>
<td>9:15</td>
<td>Arrival to Monistrol Vila railway station</td>
</tr>
<tr>
<td>9:20</td>
<td><strong>STOP 1</strong></td>
</tr>
<tr>
<td>9:05</td>
<td>Welcome</td>
</tr>
<tr>
<td>9:15</td>
<td>Geological context</td>
</tr>
<tr>
<td>9:30</td>
<td>Rack railway</td>
</tr>
<tr>
<td></td>
<td>Monistrol Village</td>
</tr>
<tr>
<td>9:55</td>
<td>Rack railway ascent to Montserrat</td>
</tr>
<tr>
<td>10:20</td>
<td><strong>STOP 2</strong></td>
</tr>
<tr>
<td>10:15</td>
<td>Risk mitigation plan</td>
</tr>
<tr>
<td>10:20</td>
<td>Rock face monitoring</td>
</tr>
<tr>
<td>10:25</td>
<td>Block joint monitoring WSN</td>
</tr>
<tr>
<td>11:00</td>
<td>Coffee break</td>
</tr>
<tr>
<td>11:40</td>
<td><strong>STOP 3</strong></td>
</tr>
<tr>
<td>11:15</td>
<td>Risk mitigation in terrestrial access</td>
</tr>
<tr>
<td>11:20</td>
<td>LiDAR monitoring</td>
</tr>
<tr>
<td>11:25</td>
<td>GbSAR monitoring</td>
</tr>
<tr>
<td>12:40</td>
<td>Free time for touristic visit</td>
</tr>
<tr>
<td>13:40</td>
<td>Lunch</td>
</tr>
<tr>
<td>15:00</td>
<td>Funicular ascent to Sant Joan</td>
</tr>
<tr>
<td>15:35</td>
<td><strong>STOP 4</strong></td>
</tr>
<tr>
<td>15:20</td>
<td>LiDAR analysis of rock mass structure</td>
</tr>
<tr>
<td>15:30</td>
<td>Massif overview and MPRG</td>
</tr>
<tr>
<td>15:45</td>
<td>Protection shed for funicular</td>
</tr>
<tr>
<td>16:20</td>
<td>Free time for park visit</td>
</tr>
<tr>
<td>17:12</td>
<td>Funicular descent back</td>
</tr>
<tr>
<td>17:45</td>
<td>Bus meeting</td>
</tr>
<tr>
<td>18:30</td>
<td>Arrival to Barcelona</td>
</tr>
</tbody>
</table>
Geological context

Regional context
Geological context

Genesis of the massif

Martínez-Rius, 2006

E. Maestro & J. Poch
Rockfall risk management in the Montserrat massif

Geological context
Rock mass and mountain morphology

Martínez-Rius, 2006
*Geological context*

Geohazards: rockfall and landslides

**Debris flood**
(hyperconcentrated flow)  
10/06/2000 event

**Superficial landslides**
Colluviums slide / flow  
03/11/2015 event

---

6th Interdisciplinary Workshop on Rockfall Protection

**Rockfall risk management in the Montserrat massif**

**Geological context**

Geohazards: rockfall and landslides

Stop 1 (Village)  
J. Corominas (UPC)  
M. Janeras (ICGC)

RocExs 2017

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**Debris flood**
(hyperconcentrated flow)

Stop 1 (Village)  
J. Corominas (UPC)  
M. Janeras (ICGC)

**Debris flood**
(hyperconcentrated flow)  
10/06/2000 event

Regiò7, 2000

**Superficial landslides**
Colluviums slide / flow  
03/11/2015 event
History of the rack railway

1881: Constitution of the company Ferrocarriles de Montaña a Grandes Pendientes
1892: The rack railway was inaugurated (steam train)
1947: During celebrations for the enthronement of the Mare de Déu, its highest number of passengers: a total of almost 274,000
1953: Serious accident and start of decline
1957: Closure of the railway
1991: The drawing up of a project that would form the basis of the current railway
2000: Project updated following the serious torrential floods of June 10th
2001: Beginning of the works for the new rack railway
2003: The new rack railway was opened on June 11th

Route of the rack railway
Ascent: 550m
Length: 5200m
Slope: up to 18%
Structures: 3 tunnels, 3 bridges
Rockfall risk management in the Montserrat massif

Rack railway
Rockfall risk mitigation

Investment: 4.1 M€ (half at the beginning + half according to surveillance)
Active & passive protection:
- 2800m fences (500 – 5000 kJ)
- 8200m steel rod anchors
- 2000m² steel grid


Rockfall risk management in the Montserrat massif

2.01 Risk management in building area

Reference events

Hotel Cisneros: Volume=4m³

15/12/2010 event

Monastery: 4 monks dead in the nursery

March 1546 event

Stop 2 (Sanctuary)
M. Janeras (ICGC)
**Main goal**

- **M1**: Large blocks
- **M2**: Slabs, sheets
- **M3**: Pebbles and aggregates

**Rockfall mechanisms**

- **Sandstone/siltstone**
- **Conglomerate**

**Rockfalls**

- Colluvium
- Shallow landslides
- Torrential floods

<table>
<thead>
<tr>
<th>Block typology</th>
<th>Detachment mechanism</th>
<th>Modal volume</th>
<th>Typical Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Stability controlled by the discontinuities (vertical joints and bedding planes)</td>
<td>30 m$^3$ – 1000 m$^3$</td>
<td>Prims</td>
</tr>
<tr>
<td>M2</td>
<td>Plastic deformation due to weathering-induced stress (thermic effect)</td>
<td>0.3 m$^3$ – 10 m$^3$</td>
<td>Plate</td>
</tr>
<tr>
<td>M3</td>
<td>Physical and chemical weathering of the matrix</td>
<td>0.001 m$^3$ – 0.03 m$^3$</td>
<td>Oval</td>
</tr>
</tbody>
</table>

Preliminary inventory of potentially unstable masses (2011)

Priorities based on interpretation of visual signs and qualitative assessment of hazard

Risk management in the Montserrat massif

Risk management in building area

Rockfall risk mitigation plan

Risk Management

Mitigation

Preparedness

Response

Land planning and Infrastructures authorities

Civil protection and Emergency authorities

Prevention for the future
Recovering from the past

Risk Mitigation

Study Stage

Identification, characterization, hazard zoning, risk assessment

Project Stage

Planning

Analysis of alternatives, sizing calculation, structural design

Construction Stage

Risk management

Implementing

Countermeasures, active and passive protection, quality control

Operation Stage

Forecast, inspection surveys, monitoring, crisis analysis

Maintenance

Optimization

cost / benefit

Risk Mitigation

Monitoring

Stop 2 (Sanctuary)
M. Janeras (ICGC)

PMRG 2013
(georisk mitigation plan)

PEMONT 2009
(emergency protocol)

"Development of a Risk Mitigation Plan in the Montserrat Massif (Central Catalonia, Spain)". In: Mikos et al. (Editors), Advancing Culture of Living with Landslides. Springer, 4th World Landslide Forum, Ljubljana, in press.
Rockfall risk management in the Montserrat massif

Overview of the 4 monitoring techniques used in the pilot tests

<table>
<thead>
<tr>
<th>Spatial domain</th>
<th>Continuous</th>
<th>Discontinuous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ground Based Synthetic Aperture Radar (Gb-InSAR)</td>
<td>Terrestrial Laser Scanner (TLS)</td>
</tr>
<tr>
<td>Scattered</td>
<td>Rock joint instrumentation</td>
<td>Surveying Total Station</td>
</tr>
</tbody>
</table>

Temporal domain

- Continuous: Extensive monitoring (remote sensing)
  - TLS
  - GbSAR

- Discontinuous: Field surveys

Rockfall Inventory

Hazard assessment

Rockfall detection

Rock face deformation

Premonitory signs?

Preliminary analysis

Urgency?

Modelling

Stability analysis

Alternatives analysis

Early warning system

Protection works and countermeasures

Volume = 7870m³

Cadireta rock needle / tower

Rockfall risk management in the Montserrat massif

2.05

Rock face monitoring
Surveying Total Station, STS


Survey: Seasonal measurement (4/year)
Results: Oscillation amplitude = 8 mm

More year cycles are needed to determine if this displacement is fully retrievable or not.

Measurement of the relative distance between prisms along main trajectory

“Foradada” 929m
“Cadireta” 899m
520 – 540 m
645m Road

Reference/prisms
Control prisms
48 m

Stop 2 (Sanctuary)
M. Janeras (ICGC)
J.A. Gili (UPC)

Field trip
Wednesday, 24 May 2017
Block joint monitoring
Instrumentation

Installation and equipment

Constraints:
- Several blocks to monitor
- Proximity of each other and to buildings
- Difficulty of access
- Minimizing the visual impact

Walking paths
Equipped path
Rope descents

Wireless network

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ZBLogger characteristics

General
- Based on ZigBee protocol (IEEE 802.15.4)
- Low power device (sleep mode ~ 95% of time)
- IGC design and production
- Low cost device (~ 110 €/unit)
- Enclosure
  - Waterproof (IP67)
- Power
  - Solar cell 0.96W
  - 8 LR6 1.5V (AA) rechargeable batteries
  - Power consumption: ~1-10μA (passive sensors)
    ~1-10mA (active sensors)

Measurement:
- Input channels: 3 single ended or 1 differential + 1 single ended
- Sensor output: voltage, current (4-20mA), resistance
- Active / passive sensors
- 16 bits sigma-delta A/D converter
- State of health (SOH): battery voltage

Communication:
- Up to 250 kbps
- Transmit power: +18 dBm E.I.R.P (max)
- Working distance: up to 1.6 km outdoor line-of-sight
- Various Antenna Options: Dipole 1/3/5 dBi
- Radio Frequency Range: 2.410 ~ 2.475 GHz
- Number of frequency channels: 14
- Transmission Method: Direct Sequence Spread Spectrum
- Modulation Method: O-QPSK

Dynamic topology for every path (best route for connectivity)
Rockfall risk management in the Montserrat massif

Block joint monitoring

Wireless sensor network WSN

<table>
<thead>
<tr>
<th>Station</th>
<th>Risk zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Block A3-6 Railway</td>
</tr>
<tr>
<td>2</td>
<td>Nostra Senyora Meteorological station and HUB</td>
</tr>
<tr>
<td>3</td>
<td>Castell del Diable Monastery</td>
</tr>
<tr>
<td>4</td>
<td>Berruga Sanctuary</td>
</tr>
<tr>
<td>5</td>
<td>Esperó Cisneros Hotel</td>
</tr>
<tr>
<td>6</td>
<td>Degotalls wall Parking</td>
</tr>
<tr>
<td>7</td>
<td>N2c05b11 column Hotel</td>
</tr>
<tr>
<td>8</td>
<td>N2c05b1 needle Hotel</td>
</tr>
<tr>
<td>9</td>
<td>Dipòsit slab Tank of water</td>
</tr>
<tr>
<td>10</td>
<td>Viacrucis Funicular &amp; path</td>
</tr>
</tbody>
</table>

Meteorological station and HUB
Rockfall risk management in the Montserrat massif

Block joint monitoring
Data collecting and managing

Unified and homogeneous management of all the monitoring projects in ICGC

- Several interfaces:
  - Manual
  - Automatic / remote:
    - FTP
    - Internet / GSM / GPRS / 3G
  - Real time / Under demand

Data collector → Data base → Web interface → Warning system

- Data query and exploitation
- Web responsive to portable devices

Results of contact sensors instrumentation

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Amplitude of annual oscillation (mm)</th>
<th>Accumulated displacement (mm/year)</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>2.0</td>
<td>-0.17</td>
<td>8.5%</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>1.0</td>
<td>-0.065</td>
<td>6.5%</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>1.3</td>
<td>0.000</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Air Temp. 36.7 °C

Toppling rate: 1E-5 rad/year

Block A3-6:
- First monitoring station
- Since October 2010
- Longest time series
- Wired (sensors – datalogger)

Rockfall risk management in the Montserrat massif

Risk mitigation for the accessibility

Reference events

02/01/2007 event
Time: 6:45
Volume: 300 m³
Effects:
Road & railway blocked

28/12/2008 event
Time: 13:45
Volume: 900 m³
Effects:
1800 people to be evacuated by cable car (finish at 21:30)
213 cars & 7 buses blocked
Recovery:
14Feb: emergency path by road
13March: railway service
27March: road without limitations

915m (top)
735m (cliff bottom)
665m (road)
550m (railway)
Retrospective (after 2008):
Precursory displacements?
Signs of instability evolution?

Photo date: 2001
Event date: dd/mm/2001
20 m³
Chronologic order
Previous event

30/01/2006
02/01/2007
300 m³
Present event

02/01/2007
28/12/2008
900 m³
Next event

03/11/2008 episode (rainfall and several rockfalls)

Photos: L. Baciero (19/05/2008)
Rockfall risk management in the Montserrat massif

Risk mitigation for the accessibility

Protective works
LiDAR monitoring Methodology

Data acquisition
(TLS ILRIS 3D, OPTECH)

Point cloud classification (CANUPO)

Vegetation
Rock

Deformation analysis
Point cloud segmentation
Alignment and comparison
(X, Y, Z, Differences)

Nearest Neighbor Technique application
30 cm
Filter per minimum detectable value

Results presentation

Rockfalls analysis
Alignment and comparison
(X, Y, Z, Differences)

Filter per difference value
Points < 0.05 m
Points > 0.05 m

Cluster algorithm application (DBSCAN)
No cluster
Cluster

Clusters extraction and volum calculation

References
Rockfall risk management in the Montserrat massif

LiDAR monitoring

Rockfall detection and analysis: Degotalls N

Monitoring Period 2007.05 – 2017.01

Rockfall inventory

3.538 monitoring days

Total nº rockfalls: 225

Accumulated nº of rockfalls vs Time
Rockfall risk management in the Montserrat massif

LiDAR monitoring
Rockfall detection and analysis: Degotalls E

Degotalls E
Dist. 220 m
Point spacing 7.3cm
2 scans
30% overlap

Monitoring Period 2007.05 – 2016.12
3.507 monitoring days
Total nº rockfalls: 126

Accumulated nº of Rockfalls vs Time

Magnitude-Frequency relationship

F = 0.250 V^{-0.764}

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LiDAR monitoring
Precursory movements: Block displacement

Degotalls N

Monitoring period: 2007.05 – 2017.01

Bock A movement evolution and main facts conditioning stability

Bock B movement evolution and main facts conditioning stability

Stop 3 (Degotalls) RISKNAT
M. J. Royán; M. Guinau; J.M. Vilaplana; A. Abellán; D. Garcia
(Universitat de Barcelona)
Rockfall risk management in the Montserrat massif

Monitoring with GB-SAR system
Results of 5 months measurement campaign

DInSAR (Differential Interferometric Synthetic Aperture Radar)

DInSAR provides a differential interferogram from two acquisitions, representing the ground motion occurring between the acquisitions with a sub-centimetric accuracy. GB = Ground Based.

From Reflectivity maps (Complex data) to Coherence Map & Differential Interferogram

Atmospheric Artifact compensation, pixel selection & parameter extraction

Example of different atmospheric profiles

Linear velocity estimation

Maximum Linear displacement

Conclusions

- GB-SAR system working at 9.65GHz. Range resolution of 1.5m, azimuth resolution of 10 mrad (eq. of 5m @ 500m range), sub-centimetric sensibility.
- 5 months of remote controlled, unattended service.
- Geometry of stepped slopes and atmospheric artifacts are a big issue.
- No movement was detected. Further campaigns to be developed
- New areas to explore: Monestir and Degotalls
Rockfall risk management in the Montserrat massif

Joint Analysis
Introduction, Degotalls and Monestir cliffs

Situation

Methodology
LiDAR acquisition → Planar Regression → Classification

Massif joint sets
Alsaker, E. et al., 1996

Degotalls cliff
Sàbat F. 2011
Field measurements
LiDAR data

Monestir cliff
Royán, M.J. et al., 2013
Bedding 17/139
Set 1 71/182
Set 2 81/225
Set 3 83/254
Set 4 73/103
Set 5 70/122
Set 6 72/144

RocExs 2017

255
Joint Analysis
Collbató cliff and Conclusions

Collbató cliff

Blanch et al., 2017

Conclusions

Joint Analysis

<table>
<thead>
<tr>
<th>Joint sets</th>
<th>Dip/Dip Direction</th>
<th>Joint Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monestir Cliff</td>
<td>Degotalls Cliff</td>
<td>Collbató Cliff</td>
</tr>
<tr>
<td>Set 1</td>
<td>71/182°</td>
<td>86/014</td>
</tr>
<tr>
<td>Set 2</td>
<td>81/225°</td>
<td>85/038</td>
</tr>
<tr>
<td>Set 3</td>
<td>83/254°</td>
<td>85/065</td>
</tr>
<tr>
<td>Set 4</td>
<td>73/103</td>
<td>78/096</td>
</tr>
<tr>
<td>Set 5</td>
<td>70/122</td>
<td>80/120</td>
</tr>
<tr>
<td>Set 6</td>
<td>72/144</td>
<td>83/141</td>
</tr>
<tr>
<td>Set 7</td>
<td>80/335°</td>
<td>80/335°</td>
</tr>
</tbody>
</table>

* Conjugate joint sets [a 180°]

References


Overview on the massif

Rockfall hazard and runout

Rockfall inventory and runout susceptibility

Sources: bibliographic, survey and field observation
Detachment points: 71 (1956 – 2015)
Trajectory tracks: 46 (1922 – 2015)


Degotalls 2007-08:
Volume 300 – 900m³
Reach angle = 36-37°

Terrain type reference value for the Reach angle

- Open, planar slope 31°
- Channelized path 36°
- Highly deflected 45° or higher

Preliminary results

- Sanctuary & Monastery building area:
  V >= 1 m³ / T = 6 years
  V >= 10 m³ / T = 27 years
- The whole massif:
  V >= 10 m³ / F = 9 events/year

Overview on the massif
Regional cartography: MPRG25k

Rockfall risk management in the Montserrat massif

Land use planning considering the geological risks

Inventory map of phenomena signs (10,000)
Risk identification
EIRG (5,000 – 10,000)
Hazard Cadastre (Data Base, GIS)
Risk prevention map MPRG (25,000)
Hazard zoning EZTPG (2,000 – 5,000)
Regional planning (50,000 – 100,000)
Urban planning (1,000 – 2,000)

Example of hazard zoning for expected rockfall of 10-100 m³

Hazard boundaries based on the angle of reach for a 10-100 m high cliff, many instability evidences and potential rockfall volumes between 10-100 m³.


RocExs 2017
### Rockfall gallery for the funicular

#### Hazard conditions

<table>
<thead>
<tr>
<th>Mass</th>
<th>&gt;1 ton</th>
<th>100 – 500 kg</th>
<th>20 – 100 kg</th>
<th>5 – 20 kg</th>
<th>1 – 5 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Massive slabs and plates, large blocks</td>
<td>Isolated blocks prone to disaggregate</td>
<td>Thin slabs or plates</td>
<td>Pebble aggregates</td>
<td>Pebbles and crusts</td>
</tr>
</tbody>
</table>

**Constraints:**
- Maximum velocity = 40 m/s (height jump of 80m)
- Railcar glass ceiling = 0.2 kJ
- Small opening of the mesh to retain also small boulders
- Landscape friendly design from external point of view
- As transparent as possible for the passengers

**Dimensioning:** 110 kJ

Under elastic behaviour (Service limit)
Rockfall risk management in the Montserrat massif

4.06

Rockfall gallery for the funicular

Mesh test

Test site: Walenstadt, Switzerland
Test date: 8-9/04/2010
Tester: Swiss Federal Research Institute WSL
Manufacturer: GEOBRUGG
Mesh: High-tensile steel wire mesh
Sample 1: ROMBO® G30/3mm wire
Sample 2: ROMBO® G30/4mm wire
Device: KTI-Frame (4 x 4 m)

<table>
<thead>
<tr>
<th>Level</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kJ)</td>
<td>20</td>
<td>45</td>
<td>100</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>160</td>
<td>160</td>
<td>320</td>
</tr>
<tr>
<td>Release height (m)</td>
<td>12.8</td>
<td>28.7</td>
<td>32</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>15.8</td>
<td>23.8</td>
<td>25</td>
</tr>
</tbody>
</table>

Maximum pulse on the supporting wires:
- Longitudinal: 197kN @ 0.066s
- Transversal: 136kN @ 0.079s
Rockfall risk management in the Montserrat massif

Structure design

Model to reproduce the test

Rockfall gallery for the funicular

Single track

Double track

Stop 4 (Sant Joan funicular)
M. Janeras (ICGC)
J.M. Velasco (AMATRIA)
D. Paret & A. Ferré (FGC)