Passive seismic monitoring applied to rock block stability in the Montserrat Massif

Marc Janeras[1#], *Albert* Macau[2], *Juvenal* Andrés[2], and *Ferran* Parera[1]

[1]*Institut Cartogràfic i Geològic de Catalunya, ICGC, Engineering Geology Department, Parc de Montjuïc, 08038 Barcelona, Spain*
[2]*Institut Cartogràfic i Geològic de Catalunya, ICGC, Geophysical Prospecting Department, Parc de Montjuïc, 08038 Barcelona, Spain*
[#]*Corresponding author: marc.janeras@icgc.cat*

ABSTRACT

The Montserrat Massif (Catalonia, NE of Spain) is a natural and cultural heritage where rockfall risk arises. Therefore, a risk mitigation plan is underway, including rockfall monitoring at different scales using different techniques. Particularly, the rock block A3-6, menacing the rack railway leading to the monastery, has been monitored since 2010 by extensometers that show the cyclic movement due to the annual thermal cycle, which is mainly recoverable, but small residual plastic derivations have been detected in a varying amount, along years. At the end of 2021, stabilization work has been carried out. The block has been monitored with passive seismic techniques before, during, and after these works in order to detect signs or evidence of evolving stability similar to previous experiences in the Alps. Two main results have been found. On the one hand, a slight difference in the recorded ambient noise between the potentially unstable block and the rear massif was detected, for both the H/V spectral ratio and the polar spectrogram. A characteristic resonance frequency of the block is observed around 20 Hz in the direction of the toppling instability mechanism. On the other hand, during the drilling works of the anchor bolts, it was possible to clearly detect when the drilling hammer crossed the rear joint of the block. This allows confirming the assumed geometry of the block and the required anchor length, as well as a qualitative assessment of the persistence of the joint and its mechanical contact.

Keywords: H/V; ambient noise; rockfall; block stability.

1. Introduction

1.1. Scope

In rock mechanics, when assessing the stability of a singular rock block on a cliff, two main analyses must be undertaken. First, the structural setting of the rock block should be determined, as well as the geometry of the joints on which failure is expected to occur. At present, this task can be done quite easily with accuracy thanks to the available geomatic technologies like laser scanning and photogrammetry supported on both terrestrial and airborne platforms like drones (Núñez-Andrés et al. 2019), (Tavasci et al. 2023).

Secondly, stability balance should be solved for the rock block in front of the expected failure mechanism. Resistance on the joints is still the main uncertainty to be determined. Joint continuity can only be estimated by some assumptions according to geomechanical measurements made on the outcrop surface, through statistical analysis for instance. Large differences in mechanical properties can result from just a few millimeters of interface differences between a closed joint with stiff and strong contact, a joint filled with soft and weak soil, or a slightly open joint without contact. Rock bridge presence along the joints delimiting a specific block is still a key factor in stability analysis (Bonilla-Sierra et al. 2015).

These unknowns about the joint properties conditioning its strength are difficult to solve by geophysical methods. Some attempts have been made using ground penetrating radar (Deparis et al. 2007, 2013). More recently, thermography has risen as a promising option for this purpose in the case of rock slabs or sheets (Guerin et al. 2019). Finally, passive seismic methods have been also used to explore the structural disposition and behaviour of large rock blocks of different types (Lévy et al. 2011, Bottelin et al. 2013a, Colombero et al. 2021). This paper focuses on the latter to test these geophysical techniques on a singular rock block in the Montserrat Massif.

1.2. Case study

1.2.1. Montserrat Massif

Montserrat Massif is an isolated mountain located 50 km away NW from Barcelona, in Catalonia, NE of Spain. It is formed by thick layers of compact conglomerate interleaved with weak layers of fine sandstone and mudstone. Differential weathering leads to its characteristic stepped relief of rocky walls and needles, where rockfall hazard arises (Janeras et al. 2023). These conditions conflict with the high human exposure by nearly three million visitors to both the Monastery placed at mid-slope accessed by road and rack railway, and the Natural Park which attracts lots of hikers and climbers. The resulting risk is difficult to be mitigated since it is necessary to combine the safety requirements for assets and people with those for the preservation of the natural environment. A risk mitigation plan has been carried out by ICGC covering all needed tasks from surveying and monitoring to protective measures implementation.

1.2.2. Rock block A3-6

The case study presented in this paper focuses on the large rock block called A3-6 by the slope inventory for rockfall risk management in the rack railway (Palau et al. 2013). It is placed on a cliff just above the railway line and below the road and parking area, as both infrastructures climb up to the monastery in quite parallel lines across the slopes. In 2009 the stabilization project for this sector identified the potential instability of this block, but not enough evidence of poor equilibrium was concluded. Instead of stabilization, geotechnical monitoring was applied. After five years, cumulative displacement was identified as a second order of the annual cyclic behaviour coupled with thermal conditions (Janeras et al. 2017). Crackmeters placed at the upper and lower part revealed the toppling mechanism with a mean annual rate of $5\cdot10^{-5}$ rad/year, being the 10% of the amplitude range of the seasonal cycle. Due to the small scale of the strain, it was supposed to be a creeping process of weakening of the siltstone level at the base of the block, and an infill in the rear joint that prevents its fully elastic recuperation.

Despite during the next five years this creeping process had been reduced, stabilization works were promoted by the railway owner to ensure security, due to the lack of guarantees of predicting a brittle failure. The main unknown for the project was the degree of stability remaining for the block. For this reason, a passive seismic geophysical campaign was performed similar to that carried out in other instable blocks (Bottelin et al. 2018, 2021).

2. Rock mass monitoring

2.1. Block and massif structure

The rock block A3-6 is quite monolithic and 36 m high and 17 m wide. Oblique photogrammetry enables obtaining 3D models of the massif and the cliff surfaces, which are very convenient for geomechanical analysis and quantitative measurements (Janeras et al. 2022) as done in Figure 1. The block is delimited by two sets of fractures very persistent in the massif, which configure the cliff faces and relief. The rear joint is oriented towards the east (93°) and has 77° of inclination. The block lies on a weak and thin level close to the horizontal, which is formed by sandy mudstones prone to weathering. Due to the erosion, the block has an overhanging morphology reaching 8.6 m of thickness at its medium-upper section. At the base, the effective thickness is around 1.8 m. Northern and eastern faces are free and enable the toppling mechanism. Finally, the resulting volume of the block is 3125 m^3 corresponding to a mass of 8281 tons.

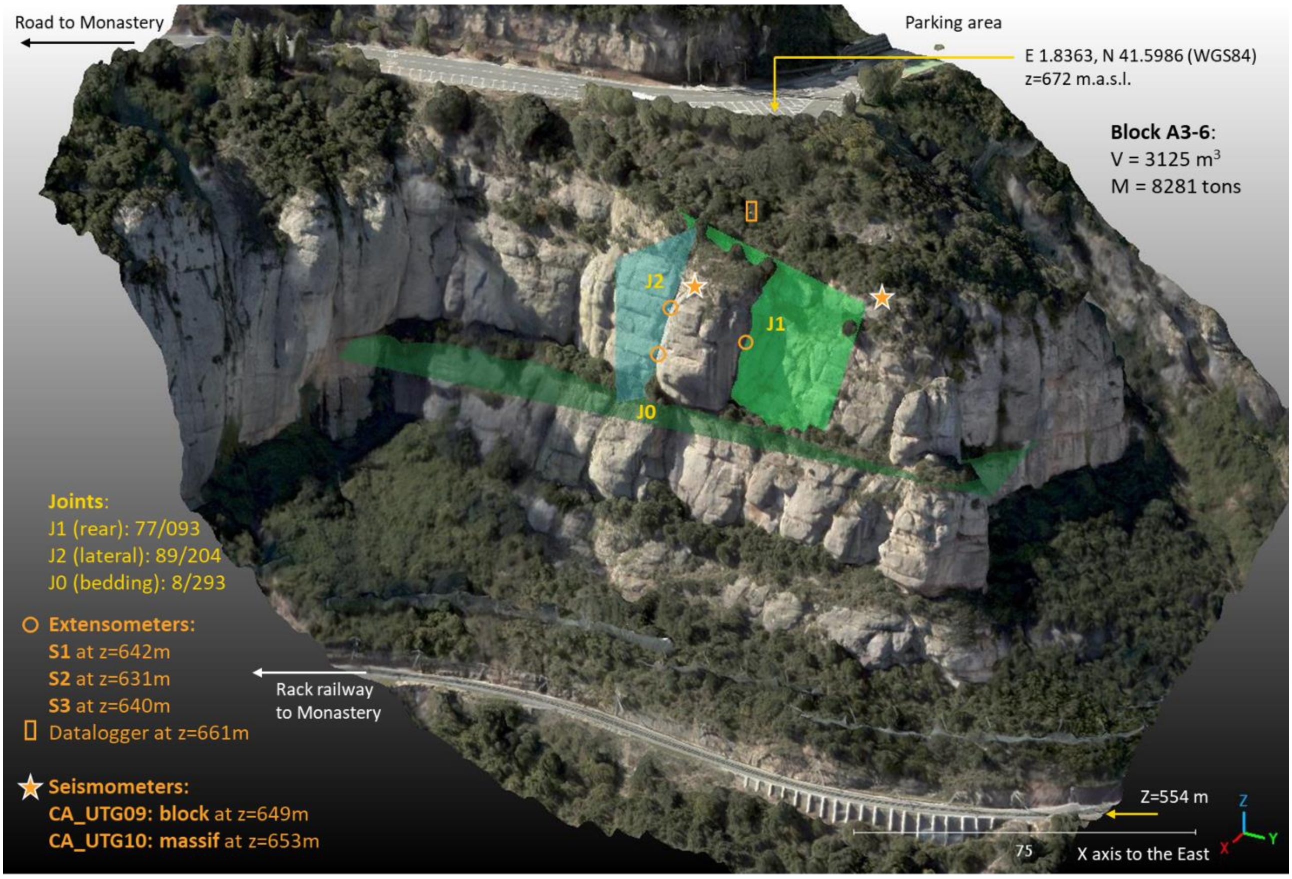


Figure 1. Structural disposition of rock block A3-6, shown on a 3D model obtained by oblique photogrammetry.

2.2. Monitoring systems

2.2.1. Precursory displacements

The monitoring of the block started in 2010 with a basic system consisting in 3 extensometers: S1 and S2 wire extensometers measuring the joint's wedge opening at two positions of different height at the left side, and S3 bar extensometer measuring the joint sliding at the right side (Fig. 1). The sensors are read every 30 minutes, and wired to a datalogger placed at the top, where there is also an air temperature sensor. This system has been recording data for 10 years, providing useful information for understanding the movement of the block and optimizing its stabilization, designed in 2020.

The three sensors show a seasonal oscillation of range between 1 and 2 mm with an annual period and an oscillation of a much lower order with a daily period. They both could be seen as an elastic behavior controlled by thermal variation: daily effect on the sensors and seasonal effect mainly on the rock mass. However, the data from the extensometers also shows a second-order plastic deformation that has accumulated over the years, as summarized in Table 1, in which it is pointed out that displacement rate has decreased over time. The difference between the movement registered by S1 and S2, both located on the same joint at different height, indicates a movement of topping, because the rotation axis of this movement would be situated at the limestone level on the block base.

Table 1. Plastic deformation registered by the extensometers during the period 2010-2020.

Sensor	Plastic movement rate (mm/year)	Accumulated plastic displacement (mm)
S1	0.17 – 0.07	0.80
S2	0.06 – 0.01	0.15
S3	0.01 – 0.005	0.07

2.2.2. Dynamic monitoring

The passive seismic monitoring has been carried out by installing two autonomous seismic stations (Fig. 2), one anchored at the top of the block A3-6 (UTG09) and another one installed at the massif, close to the cliff border (UTG10). Each seismic station (Fig.3) is composed of a Lennartz LE-3D/5S seismometer, a SARA SL03 digitizer, the power supply (battery with solar panels) and the communication system (mobile phone modem). The seismic stations were installed on October 7th, before the beginning of the stabilization works, and were removed on February 9th, when the works had already finished. During all this time the equipment was recording continuously with a sampling frequency of 200 Hz.

Figure 2. Installation on site of the monitoring devices on the massif (upper) and the block (lower).

Figure 3. Monitoring equipment of each device: seismometer, recorder, power supply and communications.

3. Results discussion

In this section, the main results are presented and discussed in two subsections regarding ambient noise firstly, and drilling monitoring secondly.

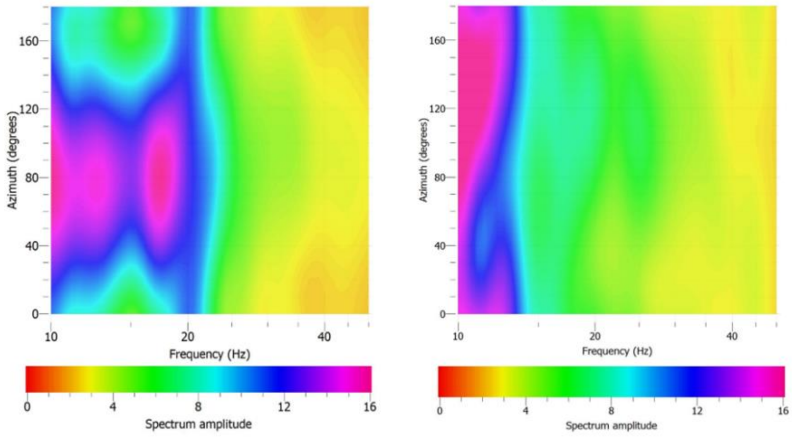
3.1. Dynamic response of the block

Seismic ambient noise recordings have been compared before and after the stabilization works. Two days are selected as representatives to show these results: October 9th and December 25th of 2021. In Figure 4 spectrograms are shown in polar format for both dates and both block and massif seismometers. On the selected days, it can be seen that the seismic noise had greater amplitude before the works than after. The main difference between the block and the massif in polar spectrograms is that the block shows a clear directionality of its vibration according to the potential toppling direction to the east, while the spectrogram of the reference massif is quite uniform in polar directionality. The preferred direction of the block does not change because the stabilization works. Despite the provided reinforcement, the structural mechanism towards instability remains visible. The block shows a natural resonance frequency within 15 to 20 Hz, with no significant changes due to the works.

From the previous recordings, H/V spectral ratios have been computed and they are presented in Figure 5 with the same scheme: before-after works and block-massif seismometers. Again, directionality appears clear for the block according to its toppling mechanism towards the east. In the massif slight directionality also appears in H/V results, which is attributed to the free face of the slope in the same direction, considering that the sensor is placed at the border of the cliff. The noise level in the recording samples before and after works is not so influential on H/V results, because it is a relative measurement of the horizontal and vertical components. For the block, there is an effect on the H/V value, increasing from factor 4 to 5. This fact can be attributed to the stabilization strategy applied, because the reinforced concrete foundation at the base of the overhanging block could have a limited the vibrational behaviour of the vertical component. However, we cannot disregard changes in the noise field as the origin of this alteration.

In the H/V spectrogram (Fig. 5), there is also a contrast between the natural resonance frequency of the block and the massif. There is a slight decrease from 18 to 16 Hz during the works, which seems not to correspond to an effect of stabilization and increase of subjection to the massif. According to the thermomechanical coupling of the block stability (Bottelin et al. 2013b) this effect could correspond to the global cooling of the environmental conditions from October to December. Crackmeters measuring laterally the opening of the rear joint (Janeras et al. 2017) show its opening in wintertime due to the block contraction, which leads to less contact with the massif.

a) Block before b) Massif before



c) Block after d) Massif after

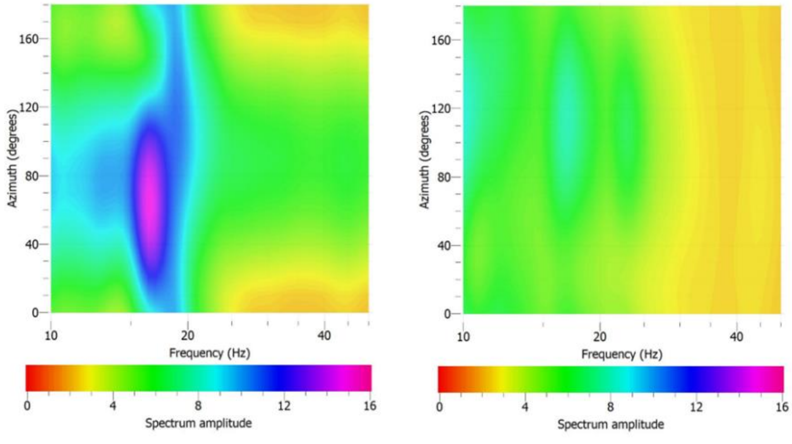


Figure 4. Polar spectrograms of selected days representative of conditions before and after the stabilization works, for both block and massif.

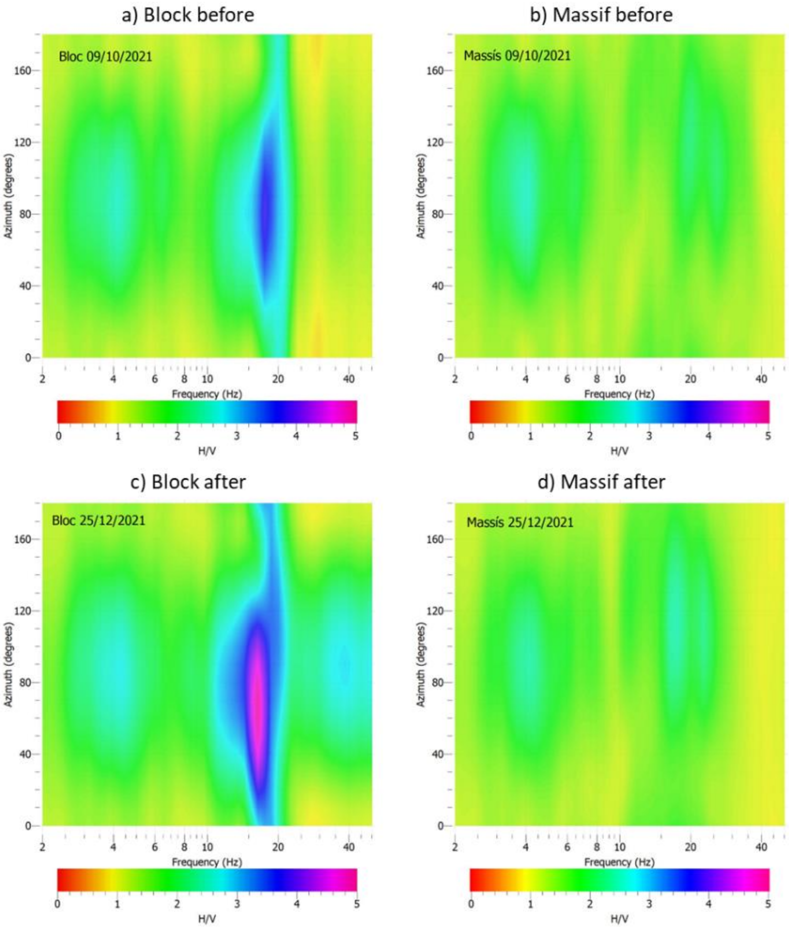


Figure 5. H/V ratio of ambient noise in polar spectrogram format for the selected days representative of before and after the stabilization works, for both block and massif.

3.2. Rock bolt drilling

Seismic monitoring was prolonged during the works. No significant change was observed like those reported in other cases (Bottelin et al. 2018, 2021), where an increase in natural resonance frequency was related to the grouting of rock bolts. It should be noted that passive rock bolts, without imposed tension, are reinforcement elements available for the block to the extent that it moves towards instability and mobilizes their resistance. Conversely, we have obtained another result applied to drilling control.

The working conditions in the mountain environment are very restrictive. Personnel access is done using ropes, while the transport of materials and machinery must be done by helicopter, as it is placed beyond the reach of conventional cranes on the road. The capacity of conventionally available external cargo helicopters is severely limited. Consequently, the drilling is carried out with a reduced column of about 2 m of run, mounted on a tubular metal structure forming a sled to be moved manually along the wall of the cliff by means of subjection cables. Under these conditions, it is difficult to ensure the exact drilling direction and inclination and to detect when the rear joint is crossed. In the case of a fissure with a small opening and light filling, it may be impossible to be perceived by the drilling workers.

Drilling equipment has a bottom roto-percussion hammer, which acts as a vibration source. Since it travels along the drilling, it allows geophysical exploration of the internal structure of the rock block. As there is one seismometer anchored to the block (UTG09) and another to the massif (UTG10), the passage of the hammer across the joint, from the block to the massif, generates a characteristic signal with decreasing amplitude, depending on the conditions of the crack. This feature was used to aid the detection of the moment when the drilling crosses the joint, marked by the red line in Figure 6. It is worth noting that the A3-6 block is monolithic and the effectiveness of the bolts lies in the fact that they cross the rear fracture with sufficient length in the back massif for achieving grip.

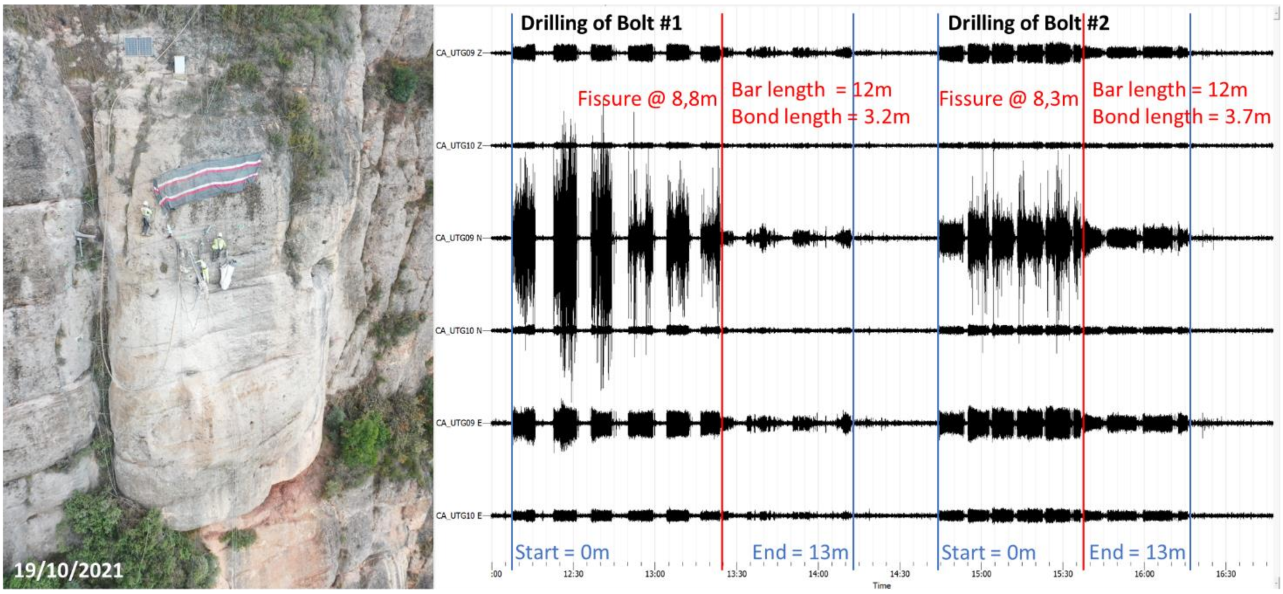


Figure 6. Rock bolt drilling in the A3-6 block, where work on ropes with drilling sled is visible, as well as the seismic sensor on the block. On the right, the vibration registers on the block (UTG09) and massif (UTG10) during the drilling of rock bolts #1 and #2 as examples of the rear joint detection al 8.8 and 8.3 m depth.

4. Conclusions

The applicability of passive seismic and H/V measurements to the evaluation of the stability of rock blocks is verified. In this application case, a wide margin of stability is concluded, which makes the results hardly visible. However, the directionality of the toppling mechanism and a slight change in structural behavior due to the reinforced concrete foundation can be observed.

It has also served to assist in inferring the length of the rock bolts, a fact of great relevance for its effectiveness, and which can be difficult to control in works built in mountain environments with light equipment. We plan to replicate this experiment in the near future to further study the advantages these analyses can provide.

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