POLITECNICO DI TORINO

Master Degree in Environmental and Land Engineering - Climate Change

Master's Degree Thesis

Towards the monitoring of underground caves using geomatics and geophysical techniques: 3D analyses and seismic response.

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ABSTRACT

In the last decade, there have been growing applications of long-term continuous ambient seismic noise systems to monitor landslides and potentially unstable rock sites. Passive seismic monitoring can help in the detection of irreversible modifications in the seismic parameters while approaching failure, and thus can be used as an early warning tool. In addition, passive seismic monitoring can highlight reversible variations in the seismic parameters and in the site microseismicity driven by modifications in temperature and precipitation rates. These phenomena help in understanding which are the external parameters driving the rock mass response and to which ones it is more sensitive.

In this work, two seismic stations were installed at the top of the Bossea cave. From the use of these stations, the goal is to understand and study which are the climatic parameters that influence the response of the rock mass in which the natural cave is settled. The thesis involves geomatics and geophysical data processing. In synthesis, the geomatic part is based on the use an open-software that allows to create a 3D model, an orthophoto and DSM model of the Bossea area and the images collected using a drone. In particular, 999 photos have been processed using OpenDroneMap software. The work was complex, because it was necessary to divide the photos in several steps to be able to download them and get the final images. For the future, as the first step to improve it could be the use of a non-open-software, both in order to compare the results, and to eliminate the limiting factors present during the process, which will be described in the thesis. In this way, it’s possible to improve not only the quality of the image, but also the work time.

Instead, the geophysics part is based on the passive seismic data, that were collected via two seismic stations. The data are referring to a long-term period between 2/12/2021 and 10/07/2022. The first step is to analyze the data, using a spectral analysis approach and to compare the seismic response to the external meteorological parameters (i.e., temperature, precipitation and wind). Microseismicity analyses are complementary performed to recognize seismic signals related to the rock mass response (mainly fracture opening and/or closing) to the meteorological data. The geophysical results highlight that the rock mass is sensitive to both rainfall intensity and temperature variations. Strong modifications in the noise spectral content are found in concomitance with intense precipitations and the peak frequency of the detected micro-seismic events are positively correlated with the air temperature.

SUMMARY

1) Introduction

In the last decade, there have been growing applications of long-term continuous ambient seismic noise systems to monitor landslides and potentially unstable rock sites. In general, the fundamental resonance frequency of the unstable compartment can be easily derived from the noise spectral content and tracked over time for early-warning purposes (e.g., Bottelin et al. 2013a **Error! Reference source not found.**; Starr et al. 2015 **Error! Reference source not found.**; Colombero et al. 2017**Error! Reference source not found.**). The detection of irreversible drops in resonance frequency values can indeed be considered as a precursor to failure. In parallel, the continuous ambient seismic noise record can contain impulsive events related to incipient fracturing, also called micro-seismic events [4]. An increasing number of micro-seismic events is expected towards failure due to fracture propagation and growth. The microseismicity of the potentially unstable compartment can be consequently tracked in time as a further and early-warning parameter. The ability of ambient seismic noise and microseismicity studies to measure and forecast the reaction of landslides and rock masses to external meteorological factors has been demonstrated in several case studies, while few attentions has been devoted to the study and monitoring of stable rock masses and other geological underground objects, as natural caves. Despite the absence of similar applications, seismic parameters might reveal useful to understand the evolution and inner dynamics of these targets.

This thesis focuses on the study of the Bossea cave, analyzing different components referred to climate change studied by means of geomatics and geophysical techniques. In the cave, an underground laboratory was installed in the years 1969-1972 by a group of volunteer cavers of the Speleological Group "Alpi Marittime" of the Italian Alpine Club (CAI) of Cuneo. This laboratory has been increasingly equipped over the years, progressively carrying out scientific research thanks to the continuous financial support of public administrations. In parallel, collaborations have started initially with the "Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture" (DIATI) of the Politecnico di Torino, later on also with the Environmental Protection Agency (ARPA Piedmont) of Cuneo, and the Department Radiation of ARPA Valle d'Aosta. Other literature studies have already produced positive and constructive data analysis on this site **Error! Reference source not found.**.

The term cave refers to any type of underground cavity, whether natural or artificial, and with very variable morphology. Caves can be small and shallow or continue for kilometers in the underground, increasing or not in parallel levels or in branches. They can have a mainly horizontal or vertical development. In Italy about 35,000 caves are known with a development of more than 5 m, for a total development of about 2500 km. The Bossea cave is a natural cavity. Its origin can be linked to geological, chemical, lithological features and hydrological phenomena of the region, and particularly due to the long-term effect of the surface and hypogeal circulation of water in carbonate rocks, particularly predisposed to dissolution.

Moreover, we have chosen Bossea cave because is an important environment that recorded several climate modifications in both its internal and external features, related to the temperature, precipitation and in general to the climate variations.
The area under investigation is located in Piedmont (North-West of Italy), in particular is the area in the valley of the Corsaglia stream, in the province of Cuneo.
This work is divided in two different sections: geomatics characterization and geophysical monitoring. From the geomatics approach, our goal was to define a 3D model of the area around the cave, while the geophysical part is focused on the analyses of the data collect from two temporary seismic stations and from meteorological stations. The on-site geophysical monitoring test lasted from 2/12/2021 to 10/07/2022.

2) Materials and Methods

2.1 The Geomatics tools

There are different types of tools that we can used in based on the different activities: in field or in laboratory. In fact, in the field the tool is the drone. With the term drone we identified a tool without pilot that was created for military applications. The drone is constituted by several components:

1) **Lidar:** is a remote sensing technique that allows you to determine the distance to an object or surface using a laser pulse, in synthesis it is a technique similar to a radar (but still has different differences compared to the radar) laser that works thanks to the pulsed light technology. They are laser used as a scanner: they can easily "read" the territory by identifying the hills, the ditches, the depth of the same and so on. All in an extraordinarily easy way: everything you need is simply to turn the laser to the territory and wait a little to scan it. Everything else is simply a matter of technique. For this nowadays it is one of the most used location and navigation systems ever. In particular, in recent years this technology is increasingly used in everything related to the mapping of morphologies: it helps to establish the differences in height between the land with a particular eye to the morphology of a certain territory.

Figure 1: Example of Lidar.

2) **Navigation sensor:** usually is the GNSS system (Global Navigation Satellite System), that is a geo-radiolocation and terrestrial, sea or air navigation system, which uses a network of artificial satellites in orbit and in synthesis in this way is possible to estimate the position. An example is the Real-Time Kinematic (RTK), that it is the technique that eliminates errors as much as possible to give you accurate results and enhanced positional data down to centimeter resolution. When the signal from satellites travels towards the receiver, it goes through 20,200 km of ionosphere and atmosphere down to Earth. The ionospheric effect significantly slows the signal and also can disturb it on the way. In addition, many factors, such as clouds, or obstacles, can affect the travel time and increase the position error. To deal with these issues, RTK comes to the rescue. For RTK, you need two GNSS receivers: one is static and called a “base station,” the other is moving and is called a “rover.” While both receivers observe

the same satellites simultaneously, the static base station is placed at a point with known coordinates (a benchmark or a point measured beforehand). Taking into account the known coordinates and receiving satellite signals, the base transmits corrections to the moving rover. This way, the rover can get sub-centimeter accurate positioning.

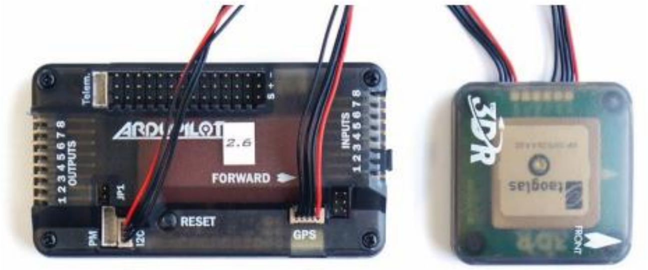

Figure 2: Example of navigation sensor.

3) **Imaging sensor:** usually is videocamera, but in based on the type of utilization we can change the type of videocamera, for example digital camera IR or thermal camera.

Figure 3: Example of camera.

4) **Supporting frame**: capable of supporting the mechanics and electronic circuits. It constitutes the main structure of the vehicle, and can be made according to the models in carbon, in plastic or even in wood.

Using the drone, we can take photos of the area that we can analyzed and study. In particular in this case, we have taken 999 photos.

Figure 4: Drone.

The second step is the use in laboratory of different software like OpenDroneMap and QGIS. The first allows to modify the photos and is able to generate the 3D model and other results. In synthesis is an open source photogrammetry toolkit to process aerial imagery (usually from a drone) into maps and 3D models. QGIS is an open-source GIS desktop application that allows you to view, organize, analyze and represent spatial data. It is currently the most widely used open-source GIS software in the world. Moreover, QGIS supports both vector and raster data. Both software are described in the section 2.5.

2.2 The Geophysical tools

Geophysical methods con be roughly divided in:

- Active methods, that need an external source provided by the user to investigate the subsurface.
- Passive methods, in which the user is only a listener of the ongoing natural and anthropic processes. These geophysical signals, and in particular passive seismic signals, may provide direct insights into the mechanical alterations of the subsurface that could lead to a failure. Passive seismic methods include site-specific spectral amplification, microseismicity analysis, and more recently ambient noise correlation. Analysis of long-term monitoring data using passive seismic methods has revealed clear precursory signals several hours or days before landslide failures. The idea of this thesis is to explore the information they can give in relation to other monitored objects, as natural caves.

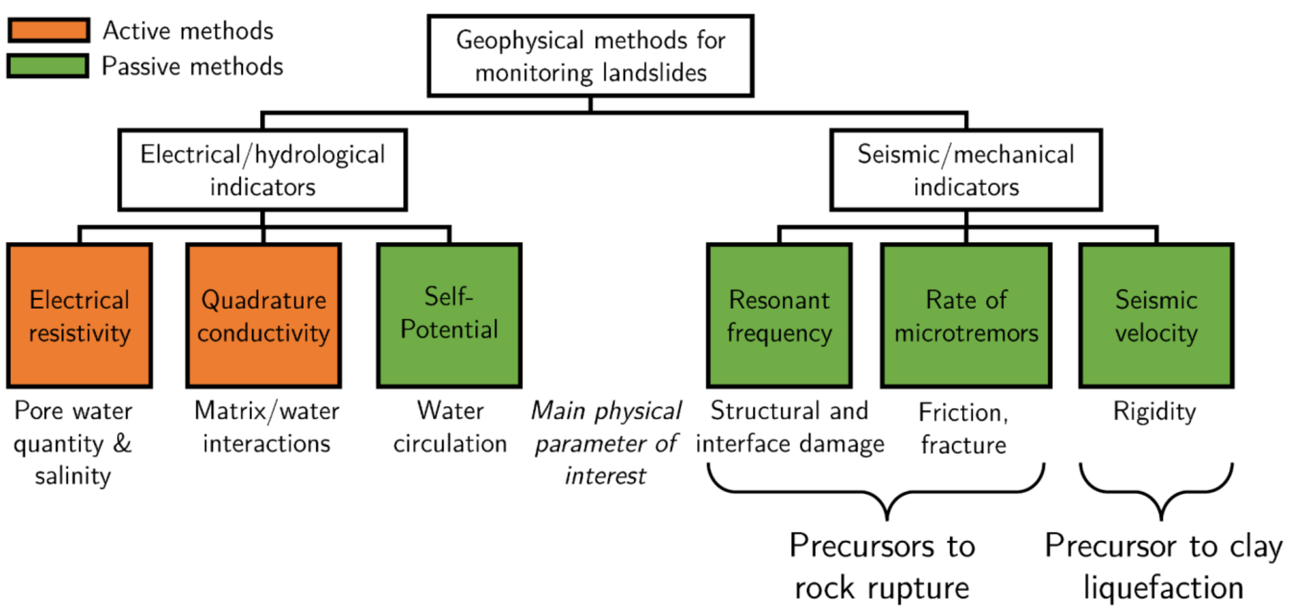

Figure 5: *Geophysical methods.*

Dealing with the instrumentation, in our case, we have decided to use two passive seismic stations constituted by four different parts:

1) **High-sensitivity triaxial geophone (Trillium Compact 20s, Nanometric)** is a seismometer with a flat velocity response from 20 s (0.05 Hz) to 100 Hz. This means that the acquired data amplitudes are reliable in this frequency band. The seismometer has a high sensitivity of 750 V/(m/s), ideal for the measurement of ambient noise vibrations. The instrument features an industry-leading tilt tolerance of 10°, making deployments very fast and efficient in various surface conditions. The benefits are: 1) Low-noise broadband seismometer performance combined with the handling and installation convenience of a geophone; 2) Ultra-low power consumption (180 mW) allows for smaller power systems and higher station reliability; 3) Exceptionally small size significantly reduces the time and effort required for site

preparation and installation, 4) Quick and easy to deploy with no mass lock, no mass centering and a wide tilt range, 5) Integrated web server facilitates instrument management.

Figure 6: Trillium Compact broadband seismometer (Nanometrics)

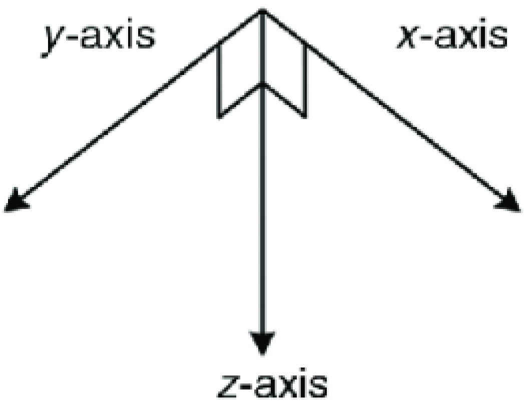

Figure 7: Three axes of the broadband seismometer

2) **Data acquisition system (Pegasus Digital Recorder, Nanometrics):** the digitizers used to sample and acquire the data recorded by the three axes of the seismometer at a sampling frequency of 250 Hz. Data are stored in daily files (MiniSEED format). Pegasus is a standalone, portable, digital recorded that reduces time in the field, the need for on-site station health checks, inventory management, and power related costs.

3) **Power supply (Pegasus SMART Battery** and Quick Deployment Kit, Nanometrics): the charge last different days, but in our case, we have used a solar panel to increase the duration to at least seven months of continuous recording for each station.

4) **GPS antenna:** for timing and synchronization between the two deployed seismic stations.

State of health and data storage of each station can be checked through the Pegasus Mobile Application and downloaded via USB connection with the Pegasus Harvester App. These tools minimize the time required to retrieve and process complete data sets and allow for retrieving several months of data in Mini SEED format along with Station XML metadata, State of Health and comprehensive project audit data in few minutes.

2.3 Noise Spectral Analysis

Spectral analysis of the ambient seismic noise recordings was undertaken to evaluate the performance of the monitoring stations, recognize the possible presence of natural resonance frequencies or high-energy frequency bands in the noise spectral content and to study their temporal evolution in comparison with temperature and rainfall amounts.

First, the power spectral density (PSD) of the noise data set was computed following Bendat & Piersol (1971) and McNamara and Buland (2004) on each component of the two stations, splitting the data in 1-hour files. Data clipping was used to reduce the influence of episodic energetic events, using an adaptive threshold fixed at four times the standard deviation of the whole detrended and demeaned signal. To further reduce the variance of the final PSD estimates, each 1-hr record was then windowed into shorter non-overlapping segments of 100 s and tapered with a 10 per cent cosine function. PSDs were then computed on each 100-s window and averaged over each hour, after correction for the loss of amplitude due to tapering.

On unstable rock masses, the computation of the spectral content of noise recordings can help in recognizing the natural resonance frequency of the site

Moreover, it’s based on considering several factors: frequency of resonance f1, whose value increases with the rigidity K and decreases with the M mass of the system, following the basic equation of a simple oscillator:

$$f1 = \frac{1}{2\pi}\sqrt{\frac{K}{M}}. \quad (1)$$

Furthermore, throughout the research history, Chen and he (1997) introduced a specific equation, for a thin beam of square section in flexible vibration:

$$fi = \frac{k_i}{2\pi}\frac{L}{z^2}\sqrt{\frac{E}{12\rho}}(i = 1, 2, \ldots) \quad (2)$$

where *ki* is a numeric coefficient depending on the resonant mode *i*(*k1* = 1.875 for the first vibration mode), *L* and *z* describe the geometry of the beam, being the length of the square side and free height, respectively, *E* and *ρ*are the Young’s modulus and density of the beam material, respectively. Following two equations, irreversible drops in *f1* values over the monitored period can be interpreted as a loss in internal or contact stiffness and therefore be read as potential precursors to failure (Lévy et al. 2010 [6]). However, even if failure does not occur, minor reversible fluctuations in resonance frequency are systematically reported in the literature. These fluctuations are interpreted as a consequence of changes in meteorological parameters (mainly air temperature *T* and precipitation *P*), which may modify the internal properties of the unstable compartments over different timescales. It should be noted that not only resonance frequency values, but also the amplitude of the spectral peaks (both in PSDs and in spectral ratios) and the azimuth of vibration can vary over time depending on weather conditions.

In our case study, in absence of unstable sectors and related resonance frequencies, the hourly PSD have been analyzed and monitored in time with the aim to recognize reversible variations in the rock mass response at the top of the Bossea cave connected to meteorological modification (temperatures and rainfall) and consequent modifications in the rock mass thermal regime or water infiltration.

2.4 Microseismicity analyses

Local rock failure and/or slip generates a release of elastic waves known as a microseismic (MS) event. The detection of these events, together with the analysis of their temporal rate and the source locations, can potentially provide useful information on the acceleration to failure and the identification of the prone-to-fall compartments and slip surfaces. In addition, similar events can be generated by the thermal expansion or contraction of the rock mass, even in stable sites. Therefore, with the study, we tried to investigate how the temperature and rainfall modifications can change the seismic response of the rock mass above the cave. For this reason, an additional important step is to analyze meteorological data from the study area to evaluate the variations of temperature and precipitation.

2.5 Processing approaches

The processing part is divided in two different works: the geomatic part and the geophysics part. The first step is to analyze the characteristics, morphology of the Bossea cave and using a drone we take photos. In particular in this case, we have taken 999 photos. The second step is the use in laboratory a software like OpenDroneMap, (https://www.opendronemap.org), in which we process the photos obtained via drone. OpenDroneMap (ODM) is an open-source software for aerial drone imaging developed by members of OSGEO, the Open-Source Geospatial Foundation, which was started about five years ago and has made significant progress over the past year. It now offers modern photogrammetry technology for drones and other low-flying image collections such as balloons and kites, and does fully automated matching, digital surface modeling, and mosaic. Stereoscopic viewing or the creation of orthophotos and maps is used, which is a process of extracting 3D information from multiple 2D views of a scene. ODM follows a photogrammetry workflow, which begins after aerial images have been captured by a drone that can perform automated flights and is equipped with a GPS unit and camera. These drone images need to be downloaded to a PC with ODM software installed. This software allows you to create not only the 3D model but also the orthophoto, DTM model and DSM model. DTM is a model that represents only the soil, instead DSM represents natural or artificial characteristics like trees or buildings.

Moreover, it’s possible to decide different options: resolution of the orthophoto, for example could be 1 cm/pixel, also the characteristic rolling shutter is imposed and if the camera has a rolling shutter and the images are taken in motion, it’s possible to turn this option to improve the accuracy of the results. At the same, being an open software, has different problem to processing the data: the first is the power of the laptop that we use, because to download this software we need four different programs and other problem is link to the memory of the software allows you to use. In fact, in our case we have 999 photos but due to a limit of a memory it's not possible to processing all photos together, but we have divided the photos in different sections and then to obtain the final results we used QGIS, (https://www.qgis.org/it/site/forusers/download.htm),other software, to merge the different sections obtained. In this way we arrived to define an external study of the Bossea cave and then it's possible to work with geophysics results. From the stations located in Bossea cave, we obtained different data that we can process in 3 different ways: Spectral analysis, Microseismicity and Cross Correlation. The data was collected from 2/12/2021 to 10/07/2022. In this work we focus on Spectral analysis and Microseismicity approach. The graphs obtained can studied in relationship with the meteorological data, so we can define the period of precipitation and the temperature variations. Furthermore, other step is to study the correlation between frequency of a certain event with seismicity, rockfall, or temperature variation and in conclusion we get the results and we are able to classify the graphs and the results.

3) The cave and the underground environment

3.1 What is a cave

The term "cave" means every type of underground cavity, be it natural or artificial formation. They can have a very variable morphology: they can be small and shallow or open up underground for kilometers, increasing or not in parallel levels, in branches. They can have a mainly horizontal or vertical development. In Italy about 35,000 are known with a development of more than 5 m, for a total development of about 2500 km.

3.1.1 Cave formation

The natural caves, generally of dissolution, have an origin that can be linked to differents geological phenomena, chemical/lithological, hydrological of the region in which they are formed, for the effect on long times of the surface circulation and above all hypogean water: In fact, it corrodes, dissolves and transports rocky material particularly predisposed to dissolution, in most cases, carbonate composition rocks. However, there are also busty caves, the formation of which is only mechanical, linked to faults and fractures due to busty movements. The phenomena of alteration of the geomorphology of an area due to the dissolution by the water of soluble rocks are called karst phenomena; Given the wide use of carbonate rocks on the outside of the earth's crust, they moderate many areas of the whole planet surface and are at the origin of most of the existing caves.

The Carsifiable rocks are mostly limestone (CaCO3) and Dolomies (CaMg (CO3) 2), but in particular climatic situations can resist karst structures in rocks that are normally so soluble that they are dissolved quickly, such as Salgemma (NaCl) or Plaster (Case4 · 2H2O). In very hot and humid regions, the dissolution of siliceous rocks, normally insoluble, for example quartz, can be verified. The times and modalities of the acts of water on the Carsifiable rocks do not depend only on the type of rock, but also on the water itself: in addition, of course, to the quantity of water and the regime with which it flows, the factors that significantly determine the '"Aggression" water to the rocks are:

- the pH, with the lowering of which the aggression of the water increases towards carbonate materials; - the concentration of CO2 dissolved in the liquid, which increases the ends of dissolution of the limestones in solution, in the balance

CaCO3 +H2O +CO2 ⇔ CA (HCO3) 2 (3)

- it can depend on several factors, including organic production and water temperature, which is the colder and the more it is capable of maintaining gas in solution;

- The temperature of the water which, in addition to determining the quantity of soluble CO2, attributes on the other hand a greater reactivity as is higher.

3.1.2 The importance of the caves

The caves have always had an anthropic importance from the origin of civilization and are currently interesting study workshops for different naturalistic and scientific aspects. They are protected environments that provide us with numerous paleontological and archaeological testimonies, but they are also environments that show phrase and singular geomorphological forms and forms. The analysis of hymn and hypogea fauna, with the numerous species adapted to underground life (many species are endemic of particular areas) have very important material for the study of biodiversity and to retrace the evolutionary history of life. In particular, they are excellent workshops to study the influence of the temperature on the processes and functioning of the ecosystems in addition, the caves are in many respects of the "time archives" and can provide enormous quantities of information on the climate of the past, providing us with reflection ideas in order to understand also the climate of the present and how it must be modified. Not to be underestimated is also the economic value of the caves. Those suitable for tourist use attract a hundred millions of tourists all over the world annually. But even those not adapted have importance both because they attract sports and enthusiasts, and because they have water resources that are increasingly exploited.

3.2 The climate of the caves

The caves have a very particular meteorology and behavior, which make them meaningful and interesting study objects. The in -depth study of underground climatology is only in its beginnings, but already shows important results. Inside the hypogean cavities there are more or less static or in circulation air masses, often saturated, water courses, influences of matter. The environment is a thermally closed system, but there are continuous and complex exchanges of energy between the rock, water and air, to be analyzed in detail to be able to understand the mechanisms that regulate them in the short term, at the day level, at the seasonal and long -term level, at the level of years, centuries, millennia.

3.3 The MSS - Milieu Souterrain surface

The acronym MSS (Milieu Souterrain surface) means the surface underground environment, the area of the interface subsoil between the soil pedogenized horizons and the mother rock below. It consists of the lattice of cracks and micro spaces between the rocky debris and in the microfractures of the mother rock itself. This environment is permeated with air and, occasionally, of water, in a similar way to the cave environment, with the sole difference that the spaces are much more restricted; This naturally determines a selection of the size of the fauna that can access it. The MSS can be in connection and connection with cave environments, constituting an extension not reachable to human beings, or be an environment in itself, distinct and independent of a larger cavity. The MSS are not mainly formations of the karst environment and see in other types of rocks (clasti from rocks) the soils that prepare better training. In general, the MSS, which is always protected and buffered by a more or less powerful layer (but in any case, of at least tens of centimeters) of soil, has many characteristics in common with the cave environment: absence of light, very small thermal excursions, relative humidity constantly close to saturation.

4) The phases of the underground climate

4.1 The light

The cave environment is characterized by the total lack of sunlight. Starting from the entrances that open outwards, there is a gradual decrease in brightness, going from a limited area, characterized by a 1/2 lighting intensity of the external one, to a subliminal area, until an area internal, in which the light intensity is less than 1/4 than the external one, until the total darkness. Obviously, it depends on the latitude, the orientation, the possible shading, the albedo of the surface and the thermal conductivity of the rock material. This is normally not significant in the energy balance of an underground system, but for some surface caves, shallow, it can have an important influence.

4.2 The temperature

The most interesting climatic aspect of the underground environment is certainly that of the temperature of the caves and its ratio with respect to the external temperatures. The temperatures of a cave tend to be known to be more stable and constant than the external ones and the daily and seasonal thermal excursions are dampened and attenuated. Often in hypogean depths the temperatures are almost not affected by seasonal trends: in the face of local annual thermal excursions of dozens of degrees, there are sometimes excursions of a few tenths of grade inside the cave. It is generally considering that the underground temperature is stationary and is around the average external annual temperature of the area. This is not always exactly true, but in most cases, it is an excellent approximation. The temperature T of the caves has two remarkable characteristics:

1) a relative constancy;

2) a particular variation with the share.

Let's see the reasons for each of the three characteristics. The constancy of T derives from the fact that the caves have an enormous thermal capacity and dampens the variations of T of the entry fluids.

1) The constancy of temperature derives from the fact that the rock has a high thermal capacity and dampens the variations of the temperatures of the incoming fluids (water and air).

2) A value linked to the quota: in the first approximation we can say that the caves have a temperature similar to the average annual temperature of the share in which they develop.

In the first approximation we can assume that the temperature of the waters that infiltrate is almost the same as the local annual average (TL), which from now on we will call TL. And therefore, that the t of the caves is also almost the same as the TL. Almost the same.

But this "almost" contains a sea of details...

$$T_{cave} \approx T_{annual\_average} \quad (4)$$

As for the local T, the Mediterranean area is all included between isothermal 10 and 20 ° C (Figure 1). Does it mean that the caves are all to the TL? Yes, those at sea level are at the TL. Palermo 17 ° C, Trieste 12 ° C, Barcelona 16 ° C, Turin 13.5 ° C ... but Turin is not at the sea level ...

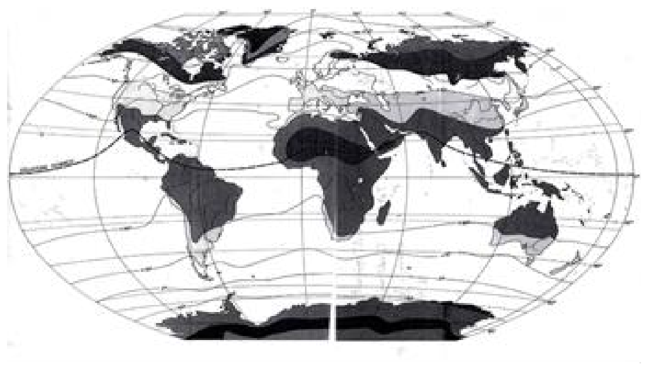

Figure 8: map of the local average T at the sea level.

In fact, corrections must be made. The main one is for the share. The external TL generally drops by 6.5 ° C each kilometer of altitude. Turin is 250 meters above sea level; So, you have to remove about 1.8 ° C. A cave in Turin has a T 12-13 ° C in the first approximation. At the same latitude we expect that a cave at 2000 meters SLM has a True t higher than 0 ° C. In general, without resorting to paper, we can operate thus to estimate the TL:

- We are looking for the TL data provided by the WMO stations closest to the interesting X area;

- We calculate for each δlat and δalt, difference of latitudes (in degrees) and altitudes (in kilometers), between point X and the WMO station;

- We estimate TL with the formula below, valid in our part;

- We meddle in the various stations.

$$T_L = T_{WMO} - 0.7\Delta Lat - 6.5\Delta Alt \quad (5)$$

4.2.1 Factors that affect the temperature

The underground system is basically composed of the rocky component and that of the ignites inside, water and air. The temperature of the system essentially depends on the balance of the temperatures of these three elements. Therefore, we must make changes to the temperature recorded in a cave. The main changes are:

1) geothermal heat;

2) Fluid selection;

3) different altitudes of infiltration.

4.2.1.1 Rock and geothermal heat

The rocks that make up the planet are heated by the internal heat of the Earth, residue by the energy accumulated during the formation of the planet, but, above all, deriving from the energy released by the radioactive decay of some elements that make them up (U, Th, K). The geothermal heat is naturally dissipating itself near the terrestrial surface, in contact with the atmosphere, with a highly variable heat flower depending on the geological characteristics of the area considered. From the depths of the earth a flow of thermal energy of 0.06 W/m2 rises. Over time, it has made all the deep rocks warm. The geothermal flow in the cave is imperceptible, because the mountains in which they are carved are to the balance with the flows of external water, which have cooled them for a long time. The flow that goes up is intercepted by the aquifer at the base of the mountain and expelled to the sources. In the end the heat flow uphill from the subsoil is dispersed in the atmosphere and in the sea, going to add up with the sun. In the deserts the ground temperature will be a little warmer than it would be if the geothermal flow was not there, just enough to give in exactly the surplus of energy to the air. In humid land, the uphill flow meets for the first real water: it keeps them hot, helping to keep them in motion.

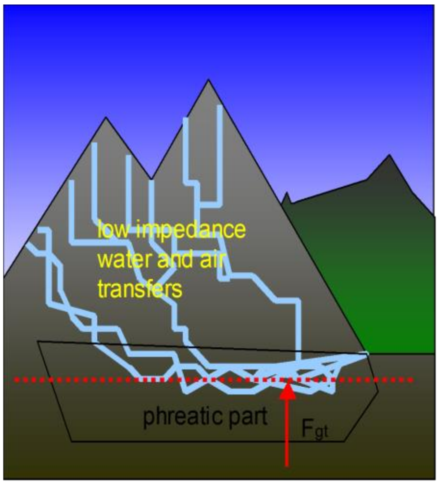

Figure 9: movement of geothermal heat

The Carsifiable rocks, as for the caves of Romina and Lambda, are however highly permeable to water, which pervades them, alters and digs. The permeation and the water flower therefore subtract its geothermal heat and profoundly modify its temperature, which does not increase in depth, as in the rocks that are not faded.

4.3 The water

As for the selection of fluids (point2) we speak of water and air. In particular, we evaluate the water for its action and for the height of infiltration which affects significantly on why the average is devoted to the TL. First reason: rainfall starts from a significantly higher share of the surface. Generally, it is admitted that their T is about 1 ° C lower than the local T of the air. Second reason: rainfall is concentrated in particular seasons: in fact, in autumn-winter the rain will be much more frequent as well as snow in winter periods than spring and summer. In fact (third reason) in areas where the snow remains for long periods, the infiltration waters are significantly warmer than the TL. When it is very cold, the water is snow, and it does not infiltrate. The infiltration begins only to the spring merger, when his T rose to 0 ° C. Under zero the water does not flow: this is the fundamental reason why sections of the ‘under-zero’ cave are very rare and very close to the outside. Finally, in particular inputs the infiltration waters may not be at all to the balance with the TL. A cave fed by a very sunny and shallow lake can be much warmer than the wait. A cave whose entrance is a large snow trap can be around zero even at relatively low altitudes.

4.3.1 Water infiltration time

During the year the constant ignition of these waters, brings and transfers the external temperature of the period in depth. If you consider the time of one year, with a quite distributed rainfall in the seasons, it can be considered that the rainwater will have, to some extent, transmitted to the rock the average external annual temperature. Obviously, although the water has a specific heat much greater than that of the rock, also assuming abundant rainfall, the mass of water will not have the power to bring a mountain to its same temperature over the course of a few years. If you think, however, with a view to thousands or tens of thousands of years, after a mass of a mass of water comparable to the mass of the rock itself, this becomes true. Since the temperature of rainfall and the external atmosphere is variable in geological times and that the times of achieving balance between rock and waters is of the order of magnitude of the hundreds/thousand years, it would be more correct to consider the temperature of the caves As in a state slightly blurred compared to the average annual local temperature present. The cave holds a residue of "memory" of the temperatures of the past in some way and in di move. Of course, there are exceptions and cases in which the underground temperature differs from the local average annual one: for example, where a part of the rainfall takes place in snow -sized form and where for the year the external water icy; In those cases, although the external temperature can be very below 0 ° C, it will not be "transported" in depth, since the water is blocked outside solid form. The temperatures of caves found in these places (typically with high latitudes or at high altitudes, above 1500 m a.s.l.m. as for Romina and Lambda) are meaning higher than external average annual temperatures. The influence of these waters will only occur at the time of the merger of the ice, when, sometimes, there are strong lowering of the underground temperatures, due to the cold of the cold waters from thaw, in contrast with the heating of the external atmosphere, which exceeds the limit of 0 ° C. In summary, therefore the waters that infiltrate the rocky embankment descend in depth quite quickly and have a very low temperature according to the altitude of infiltration and the seasonal situation.

4.3.2 Example of cooling a karst cave

We calculate the methods of cooling a karst mountain, taking up the previous example. Suppose the rock is initially at 10 ° C. We have already calculated its thermal capacity, it is 107 gj/° C. Now let's make rainwater flow on the basis of 100 kg/s, a quite typical rainfall of temperate areas. Its average annual temperature is for example 20 ° C, there was a heating of the climate. We have already seen that, in a short time, it can nothing. But now we make it flow for centuries, for millennia. In one-year 3x109 kg pass, each of which has thermal capacity of 4200 j/kg/° C. Also knowing that the mountain mass is 10^13 kg and using this formula:

$$X = \frac{C_{acq}\ M_1 T_1 + C_{ro}\ M_2 T_2}{C_{acq}\ M_1 + C_{ro}\ M_2} \quad (6)$$

We can calculate the temperature and see that in a year it has risen by 12 thousandths of grade.

So, we can say that when the mass of water flowed there is greater than it, which happens after three thousand years, everything will have taken on a temperature close to the average of that of the flowed water. Here we discovered what the temperature of the caves is: it is an accurate average of the temperatures of the waters that have flowed underground in that region over the past centuries. In the non -limestone mountains, where the water cannot flow but only to accumulate, immobile, the rock manages to preserve its heat.

4.4 Air

As a fluid (point 2) we can also consider the air circulating in enormous masses in the caves. The volume of air that flows into the caves is in many cases of significant courses. But this amount of air, which, entering and circulating, "introduces" the temperature present outside, has an often-awarding thermal capacity compared to that of the rocky mass that forms the cave. It can instantly change the temperature, especially near the entrances of the cavity, but, in contact with the walls, it soon loses its ability to alter the temperature. The temperature flows are therefore influenced by the thermal capacity of the air flows for the variations of a few minutes; For greater times it is the rock that dominates. If a large variation in temperature, such as the average seasonal thermal excursion of climates, such as the Piedmonts one, the difference of temperature measured in a type cave will only be of a few tenths of degree. The air circulation, however, can have a meaningful influence on the temperature at the local level, in particular areas of the hypogean rhetorical: the hot air tends to be in the end from the upper inputs in summer and the cold air with lower entrances in winter. This changes the temperature near the openings of the caves that work from aspiring holes in the winter.

The underground routes of the aerial currents are strongly influenced by the resistance that the cave, with its walls and its narrow -minds, exercises on the flicker: depending on the morphology of the cave we will therefore have preferential air paths (avoiding the narrow), more currents or less fast in different areas of the same cavity, areas of air static, particular condensing phenomena due to sudden changes of pressure or places where current temperatures intersect. A more in -depth study on the air allows us to talk about dry air and humid air. But as far as the first is concerned, his study in an environment like the cave is not very important as in a cave there is always humidity and water vapor.

5) Case Study

The work of this thesis focuses on the study of the Bossea cave, which is a natural karst cavity. Discovered and explored in 1816 and it was opened to the public on 2 August 1874. Moreover, since 1969 it has housed a karst laboratory of the Italian Alpine Club, which investigates phenomena, including biological ones, still taking place in the cavity. In fact, actually is one of the most important departments of excellence of the Polytechnic of Turin, to study climate change. The cave constitutes the terminal sector of a large karst system that develops in the Maudagna-Corsaglia watershed.

Figure 10: Position of the Bossea cave and the two Stations.

The cave is divided in two zone: a lower area characterized by impressive dimensions and an upper area consisting of a complex of narrow galleries developed on superimposed floors, with the two parts separated by the waterfall of Lake Ernestina. The lower area, about 900 meters long and with an ascending difference in height of 116, is equipped for tourist visits and crossed by a stream whose flow rate varies from 50 to about 1500 liters per second. To get an idea of the phenomena involved, note that the stream transports 5 million cubic meters of water every year which contains an average of 50 mg / l of dissolved calcium carbonate for a total of 750 tons of rock removed annually by the karst system.

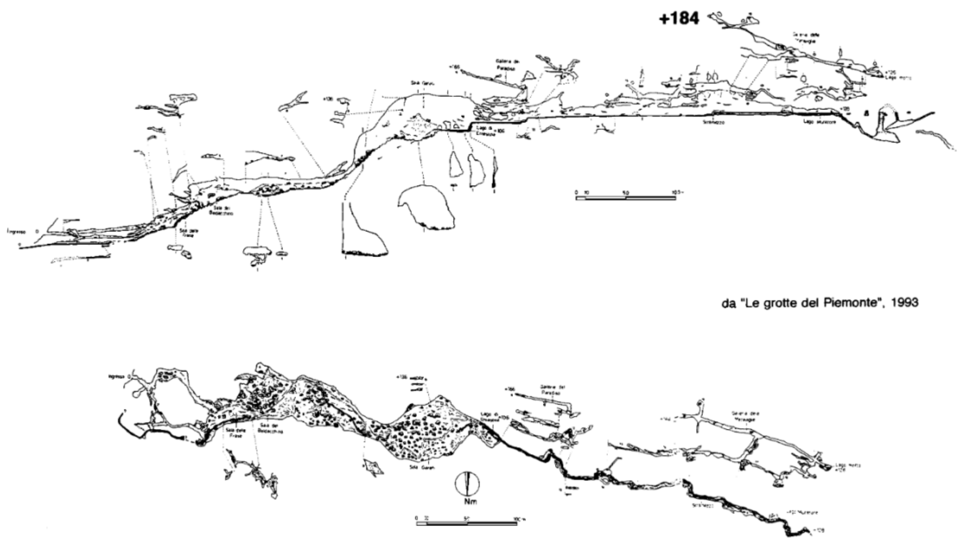

Figure 11: Bossea Cave.

Instead, outside of the cave two seismic stations were deployed.

Figure 12: Photos of the installed seismic stations.

6) Characteristics of Bossea cave

The origin of Bossea Cave can be linked to geological, chemical, lithological, hydrological phenomena of the region in which it was formed, due to the long-term effect of the surface and above all hypogeal circulation of water. In fact, water corrodes, dissolves and transports rock materials particularly predisposed to dissolution. In most cases, these rocks are of carbonate composition.

First of all, we defined what a karst cave is and its characteristics by evaluating its strengths and weaknesses, describing in particular the action of water, from sources to springs to aquifers. In karst rocks, the water is organized into water courses, sometimes real underground rivers, which run through huge tunnels of several meters in diameter and several kilometers of development. The waters of underground courses move in the same way as surface water courses: like these, they are subject to floods caused by surface precipitation (which arrives in the cave with a certain delay, due to the slowness of infiltration), and are able to excavate and erode the rock with mechanical abrasion processes, they can carry sediments of various granulometry and can create alluvial deposits inside the caves. The saturated zone of a karst system has a development and a depth that depend on the geological structure: at times the saturated zone can be of very small thickness, or absent, as in karst systems "suspended" on the base level, at times it can have hundreds of meters thick, and constitute an immense and precious water reserve. The most superficial zone of the saturated zone, called epi phreatic zone, undergoes seasonal variations and can go back up to several tens of meters in the wettest periods: it is a very important zone for the formation of caves, because, thanks to the Boegli effect due to the mixing of waters with different chemical compositions (rainwater and deep waters), it is here that the largest galleries are formed. Below the epi phreatic zone, the waters of the saturated zone move very slowly and can remain within the karst aquifer for tens or hundreds of years, before seeing the light in the springs again. This means that karst waters are very vulnerable both to pollution (a pollutant could remain inside the aquifer for decades), and to excessive exploitation (the emptying of the saturated area could take decades for the reconstitution of the primitive level of waters): they are therefore precious reserves, but to be protected and exploited with great caution.

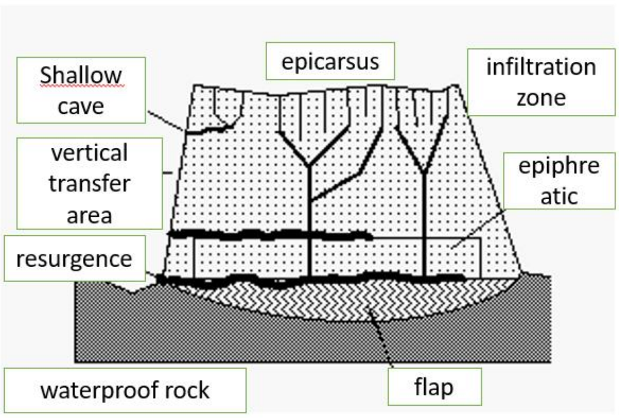

Figure 13: Subdivision of the subsoil.

Furthermore, other aspect that we can introduce are the groundwater leaks to the surface that are called springs. If the origin of the water is unknown or comes from widespread absorption, and resurgences if they are instead the coming of water courses swallowed further upstream. The springs can be classified in various ways, depending on the flow rate, the constancy of the flow or the geological characteristics that determine their formation.

7) Results

Using geomatic and geophysical tools, it's possible to estimate different results. The first approach was generic, to explain and study the external situation and then via two seismic stations, the goal was to define the different situation. Obviously, there are aspects that can impact map accuracy:

1. Time: Weather conditions have a direct impact on photogrammetry results, so it's important to consider cloud cover, wind speed, humidity, sun altitude, and other factors that affect UAV stability and terrain lighting.
2. Cameras: Larger and better sensors produce less noise and more clearly focused images. Also consider that roll-up shutter cameras produce distorted images when the UAV is in motion, so global or mechanical shutter cameras are recommended for mapping work.
3. Flight altitude: The higher the flight altitude, the larger the image footprint and GSD. The resulting GSD larger the accuracy will be decreased as there will be less detail in the recognizable features. When a smaller GSD is required, an altitude of 3 to 4 times the height of the highest point is recommended.
4. Flight Speed: has a special effect in cameras with rolling shutter, while those with global or mechanical shutter tend to reduce this effect. UAVs equipped with RTK positioning systems are also affected by speed, but with hovering over each photo taken, excellent accuracy can be achieved. If, on the other hand, you move during each photo shoot, accuracy will be limited by two factors: the speed at which you are moving multiplied by the 1 second increments of RTK.

7.1 3D model

3D model was obtained using a OpenDroneMap software, via 999 photos made with the drone. The combination of these photos, it's made step by step, because to upload all photos together was impossible, for this reason the solution was to work 150 photos for every step. Several attempts were made to understand that 150 photos were the correct number. A latest generation HP computer was used to process the images, in particular with a core i7 processor, with a 1TB flash memory. The time to process the images was on average 45-50 minutes, when he got to work with 150 images. In the previous cases, which had a negative outcome even the process lasted 4-5 hours. Obviously, an important component is to have a stable internet connection that allows you to work at a high speed. In order to use the OpenDroneMap software it is necessary to previously download other software: Python, Virtual Box which must remain open during image processing and Docker Quick Start. Once downloaded and opened on your computer, the internet interface of the OpenDroneMap software opens. Initially the first step is to understand how many images to be processed, the second step is to understand what you get and what are the characteristics set by default by the software and also the type of resolution. After a first test, it was decided to modify the properties by introducing a resolution of 1cm / pixel, to set a Dem resolution float equal to 1 and to also impose the rolling shutter. In this way the models obtained, orthophoto, DTM and DSM models have been made with a higher quality than the initial one, even if as you can see in the figures, the resolution is not detailed, as there are some white areas.

Figure 14: First 150 photos to create an orthophoto of Bossea cave.

Figure 15: Second 150 photos to create an orthophoto of Bossea cave.

Figure 16: Third 150 photos to create an orthophoto of Bossea cave.

*Figure 17**:** Fourth 150 photos to create an orthophoto of Bossea cave.*

Figure 18: Last 150 photos to create an orthophoto of Bossea cave.

The next step was to merge all different orthophotos that we have obtained:

Figure 19: Orthophoto of Bossea cave using 999 photos.

To obtain this result we use QGIS software, in which was possible the combination all partial orthophotos. In this orthophoto, the external area of Bossea cave and the entire external extension are seen. Other result that it's possible to see, is the realization of the DSM model:

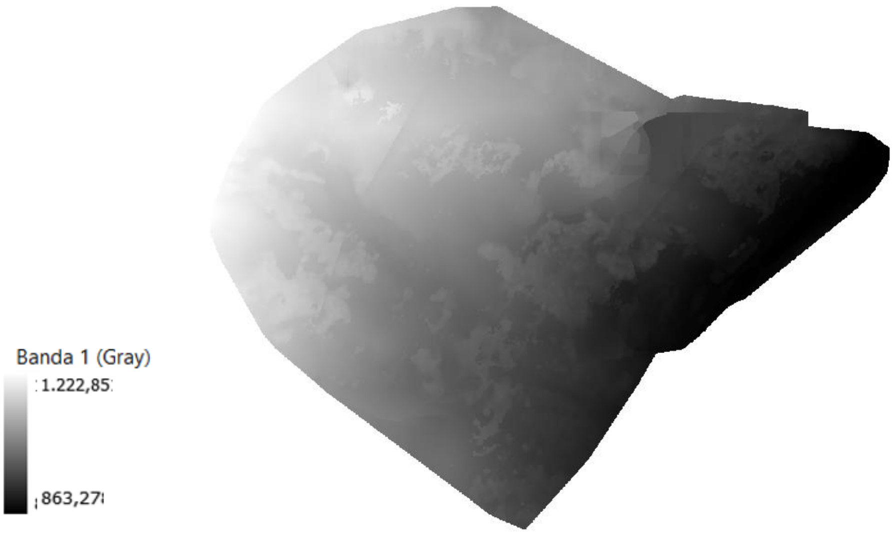

Figure 20: DSM of Bossea cave with the legend of the colours.

In conclusion, the goal was obtained a 3D model of the external area of Bossea, for every slot of 150 photo, introducing in the software OpenDroneMap.

Figure 21: Example of 3D model of the first 150 photo.

7.2 Geophysics results

Ambient seismic noise, the data acquired by the two seismic stations, were processed in Matlab, to obtain different graphs that represent the hourly Power Spectral Density (PSD) of the East, North and Vertical components of each station, from 2/12/2021 to 10/07/2022. An example is given in Figure 22 for Station 1 (N component). The average PSD of each hour of recording is plotted in a color scale from blue to red, depending on the amplitude of each frequency component.

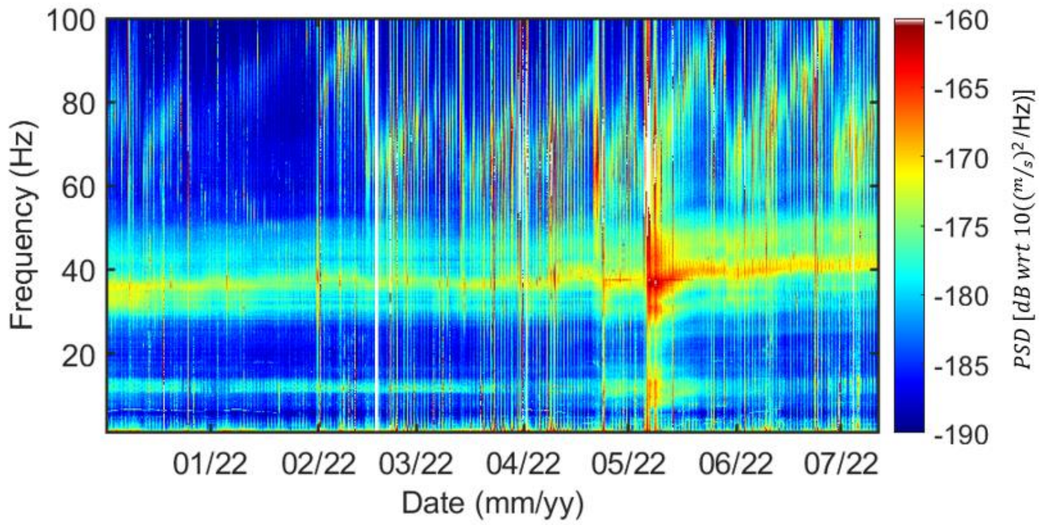

Figure 22: Hourly Power Spectral Densities of the N components of Station 1.

The next step was to study and interpret the recorded spectral content, for this reason the meteorological situation was analyzed over the same time period. In particular, the available meteorological stations (ARPA PIEMONTE) close to the site are:

- **Serra**: including precipitation and temperature measurements;
- **Frabosa Soprano**: only precipitation measurements;
- **Borello**: including precipitation and temperature measurements.

Stations	Geographic coordinate (X)	Geographic coordinate (Y)	Altitude	Distance from Bossea cave [km]
SERRA	UTM X, 412659 m	UTM Y, 4904107 m	975 m s.l.m.	6,6
FABROSA SOPRANA	UTM X, 407216 m	UTM Y, 4903242 m	683 m s.l.m.	5,8
BORELLO	UTM X, 406884 m	UTM Y, 4897585 m	1005 m s.l.m.	37,8

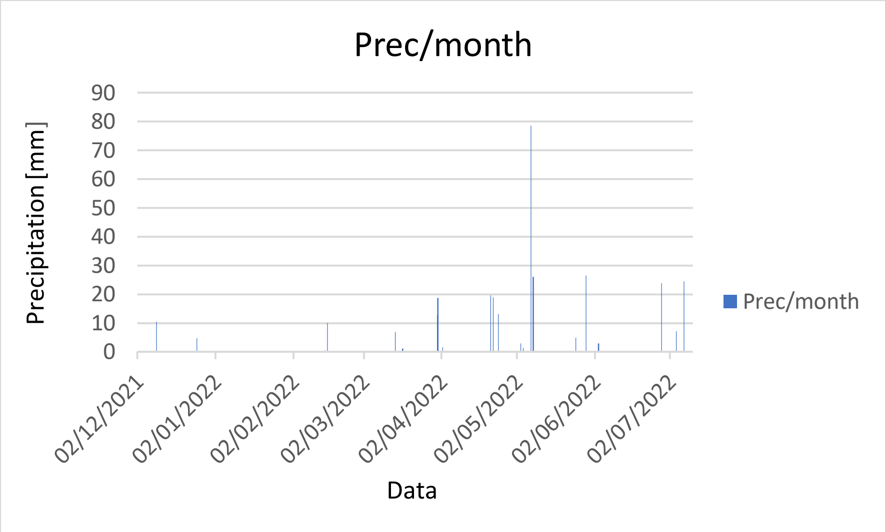

Figure 23: Precipitation situation from Serra station.

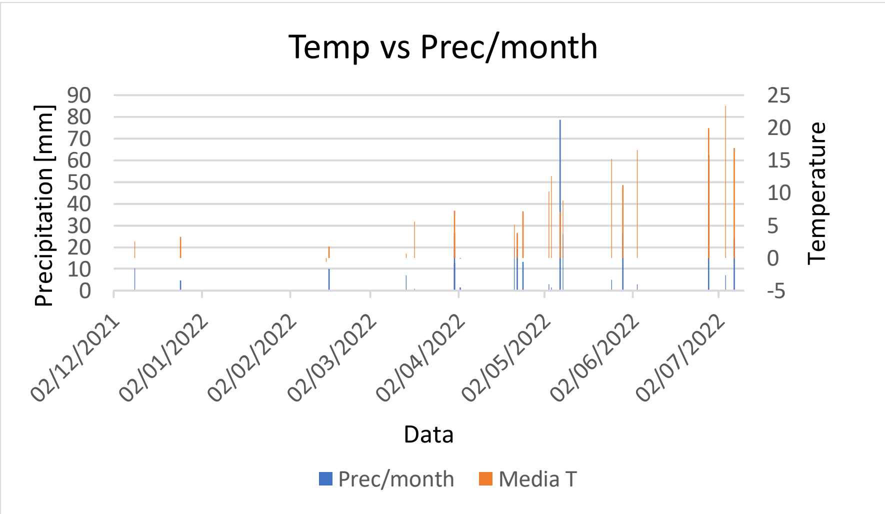

Figure 24: Temperature situation for every month from Serra station.

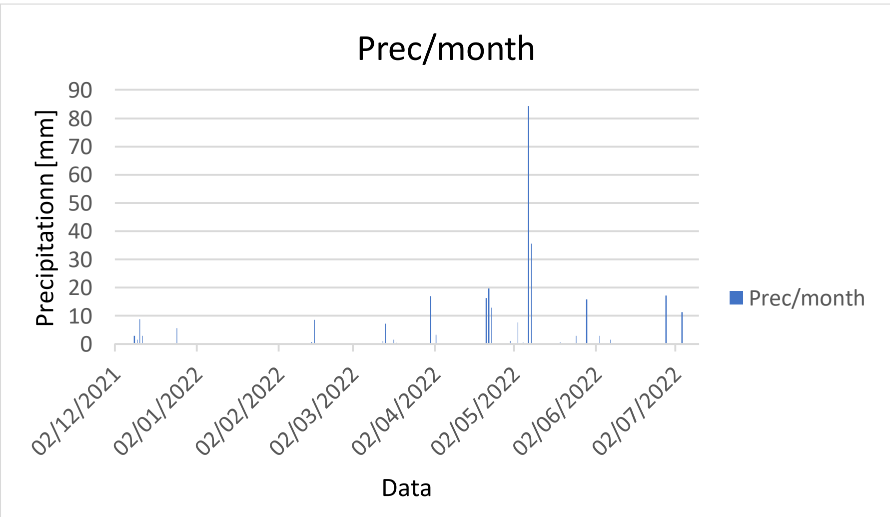

Figure 25: Precipitation situation from Frabosa Soprano station.

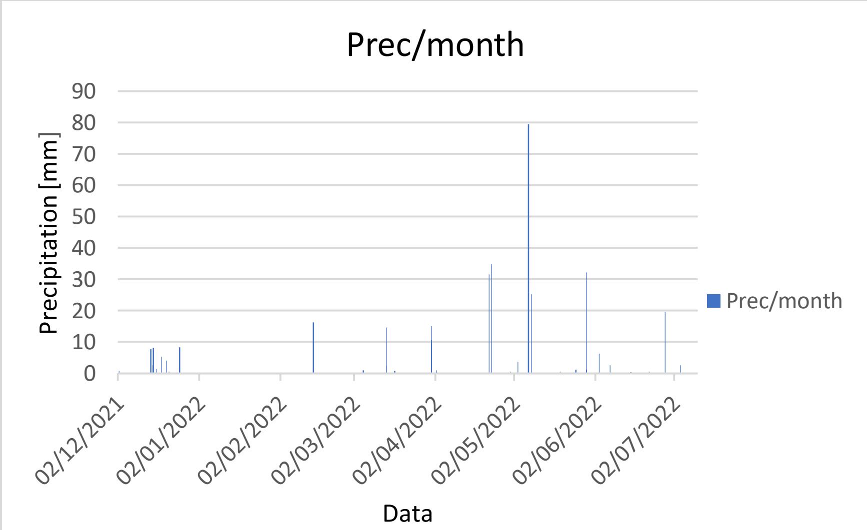

Figure 26: Precipitation situation from Borello station.

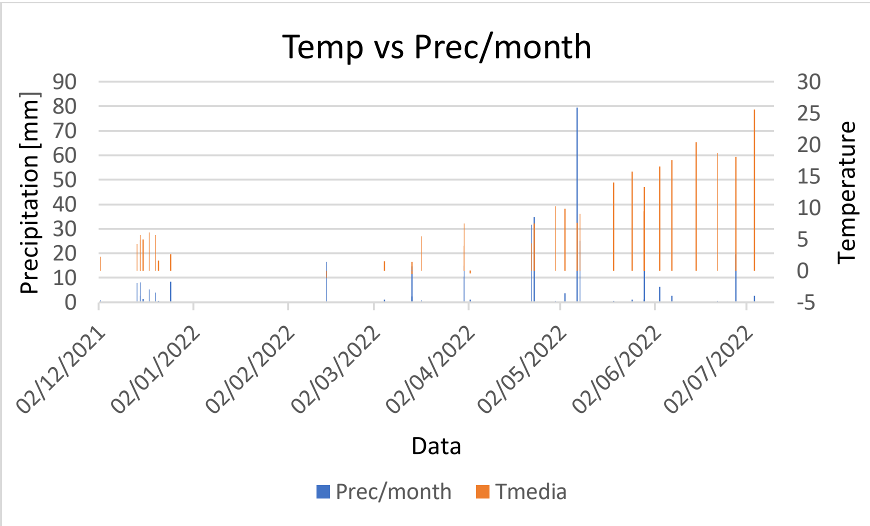

Figure 27: Temperature situation every month from Borello station.

In order to have a complete study of the meteorological situation, the wind was also taken into consideration, as a factor that can cause changes in the slope of the cave. In particular, the data are taken from two different meteorological stations: Monte-Malanotte and Rifugio Mondovì.

Stations	Geographic coordinate (X)	Geographic coordinate (Y)	Altitude	Distance from Bossea cave [km]
MONTE MALANOTTE	UTM X,403783 m	UTM Y,4901595 m	1735 m s.l.m.	4,2
RIFUGIO MONDOVI'	UTM X,398757 m	UTM Y,4894142 m	1760 m s.l.m.	10,2

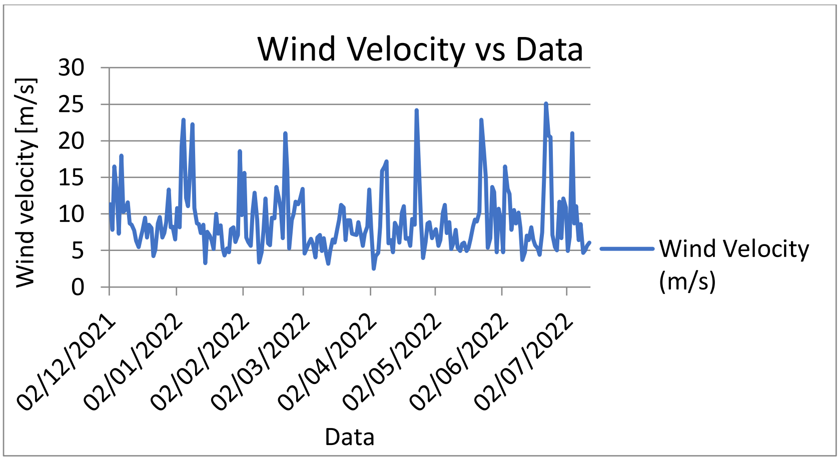

Figure 28: Wind situation every month from Monte-Malanotte station.

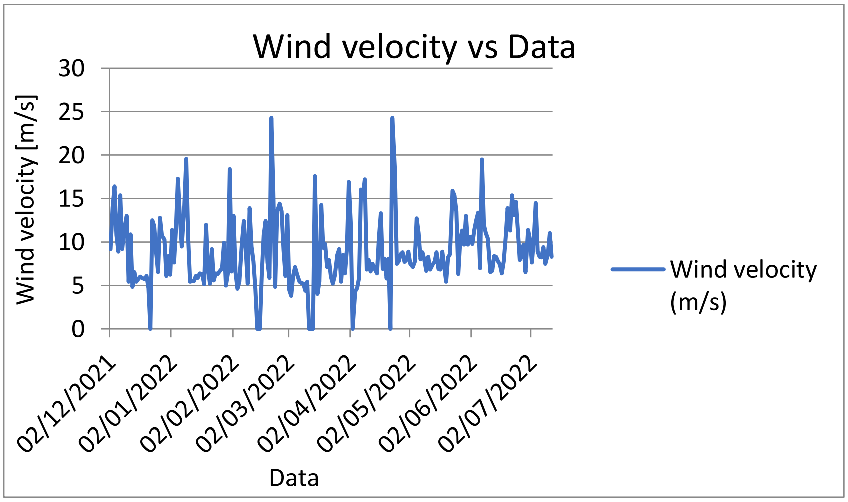

Figure 29: Wind velocity from Rifugio Mondovì station.

As stations, the only ones with wind data are: Monte Malanotte and Rifugio Mondovì. Mondovì Refuge has higher speed values than Malanotte. Comparing with the PSD_time E / N the curve at low frequencies could be linked to the wind, since at the beginning of December and for almost all of January there are high wind values higher than 10 m /s. Furthermore, April turns out to be a windy month and in fact the PSD shows a slight curve between the months of April and May.

Moving on to a first comparison with Figure 23 it's possible to notice that in the dates between 5-8 May there is a strong precipitation recorded by all 3 stations which matches the peak present in the PSD graph. In particular, for the Serra station the amount of precipitation is 316.6 mm, instead for Frabosa-Soprano is 302.6 mm and for Borello is 344 mm. The low frequency curve present in the periods of December and January does not seem to be connected to rainy or snowy events as in these months there is no abundant rainfall, on the contrary in the month of February they are completely absent and in general it appears that in the months December-January-February rainfall is almost zero compared to March-April-May-June. So, from this it can be deduced that there is very little snowfall and also an increase in temperature in the last period. Furthermore, before the peak in early May, the PSD time graph shows a slight peak due to an increase in precipitation towards the end of April.

The highest frequency peaks in the range 50-100 Hz seem really sensitive to temperature variations, as observable in the hourly comparison between temperature and precipitation and PSD results (Figure 30), in which Borello station is taken into consideration. As can be seen from the graphs of Figure 30, between a rainy or snowy event and the seismic response there is a delay of one day to one day and a half. This leads to interpret the measured seismic response as the effect of water infiltration within the rock mass at the top of the cave.
The rock mass seems therefore very influenced by temperature modifications and water circulation. In particular, the thermal effect on the seismic measurements is interpreted as due to the presence of fractures. Increasing temperature at the end of the winter season induces thermal expansion in the rock mass. The thermal expansion of the rock mass reduces the opening of the fractures. As a whole, the rock mass can be considered more rigid and compact, thus the detected frequency is increasing as a consequence of stiffness increase. On the other side, the major variation in the seismic response is linked to a precipitation event. Water seepage and circulation in the rock mass alter the rock mass seismic response for several days after the precipitation events.

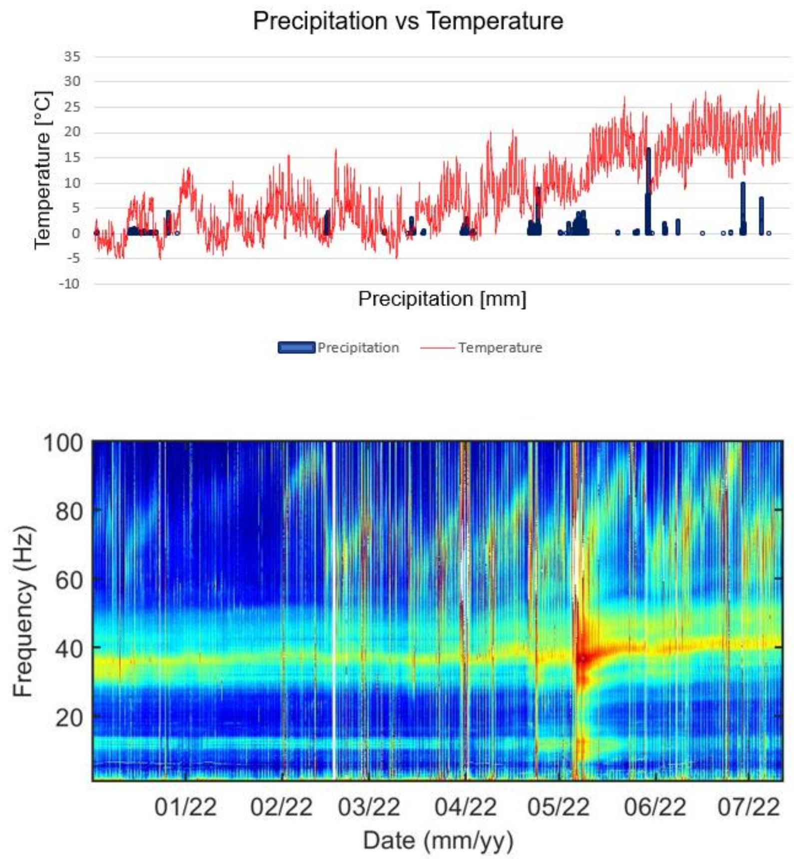

Figure 30: Comparison between PSD N_time and meteorological variations.

Similar considerations can be made on the microseismicity results shown in Figure 31. The central frequency of each detected event is plotted in Figure 31, to be used as a rough classification method to distinguish natural events related to the rock mass behavior from other types of seismic sources.

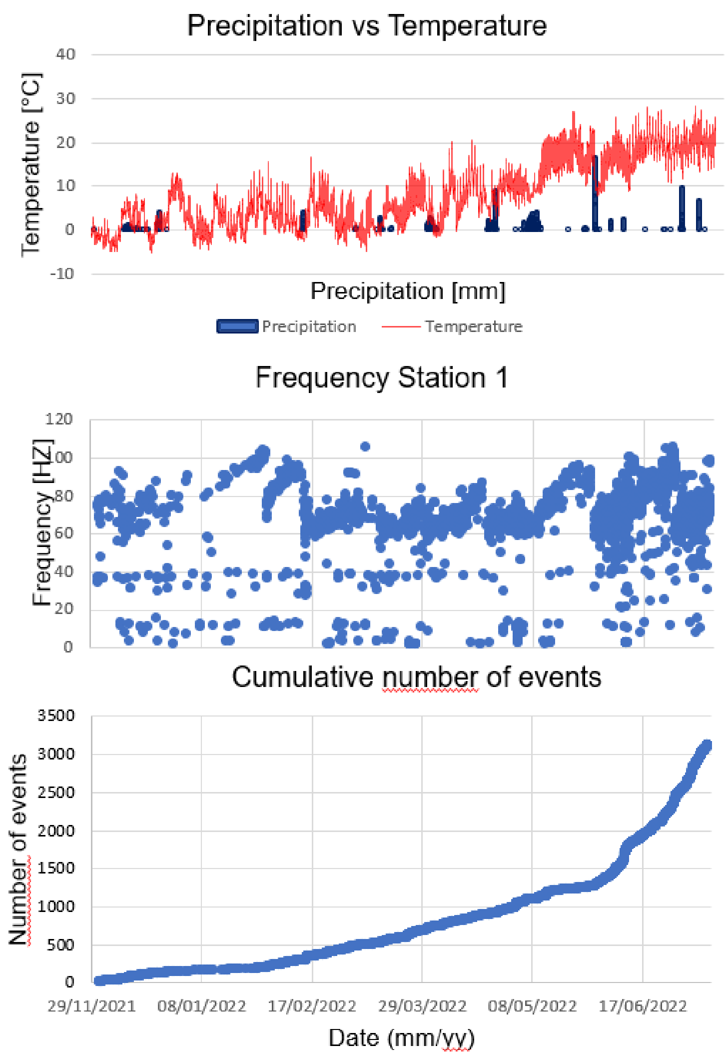

Figure 31: Comparison between number cumulative event, frequency of the events and climate variation.

Considering the seismic event frequencies, three main different classes of events can be detected:

- **Local and Regional Earthquakes:** having a central frequency below than 20 Hz. For example, in the Figure 14, the seismic event happened in 18/12/2022 is verified to be an earthquake with epicentral location close to Milan from the catalogue of Earthquakes in the Euro-Mediterranean Region (https://www.emsc-csem.org/Earthquake/europe/). Due to the fact the deployed broadband sensors have high sensitivity, many regional and local earthquakes were recorded during the monitored period. These events do not carry information about the rock mass variations and should be therefore excluded from the analysis of the event rate related to the rock mass.
- **Rockfall events:** all phenomena having a peak frequency between 20 Hz and 50-55 Hz showed a long duration. These events were consequently interpreted as due to small rock falls and slides occurring on the slope.
- **Rock fracturing:** all events in which the frequency is over 55 Hz. These events show variable central frequency with reversible modifications that are driven by temperature. In addition, from Figure 31 it

is possible to note that the number of events and their frequency increase if there is an increase in temperature. As a consequence, we can interpret the rock mass as highly sensitive the thermal dilation and contraction phenomena, in agreement with spectral analysis results.

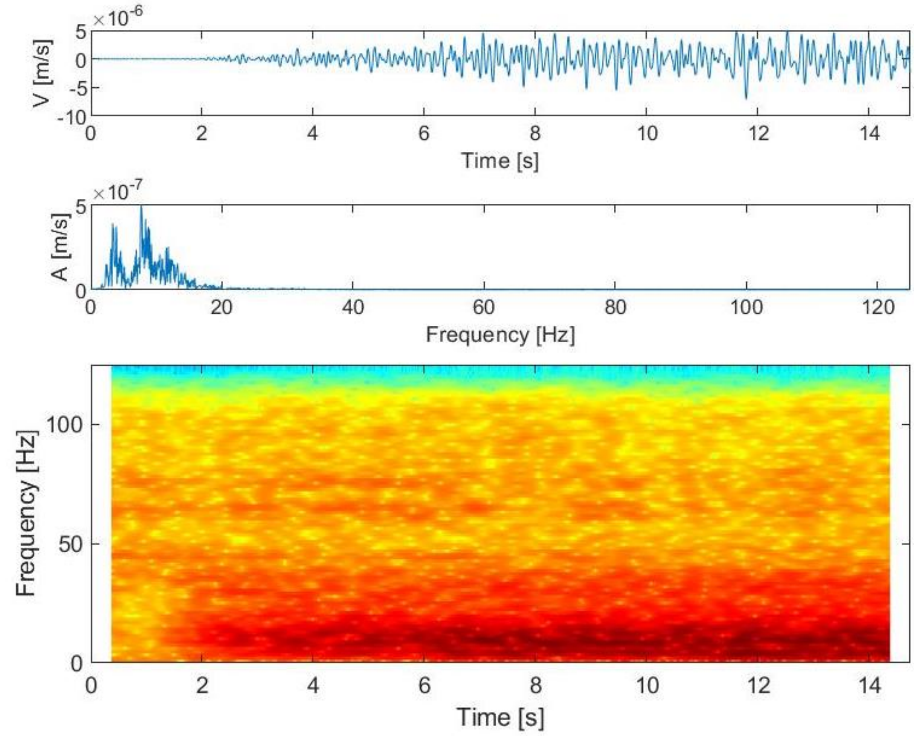

Figure 32: Example of earthquake recording.

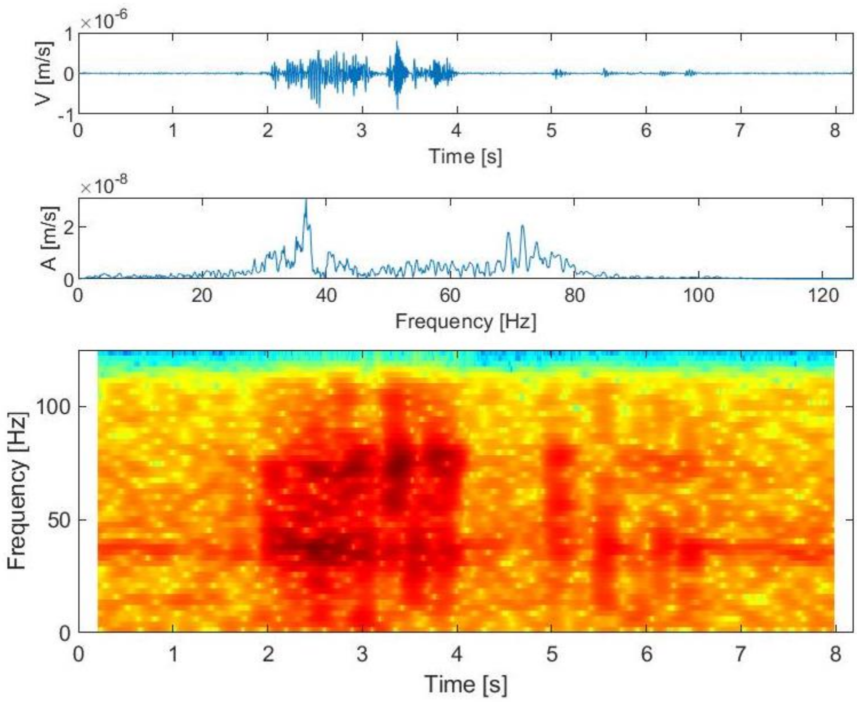

Figure 33: Example of Rockfall activities.

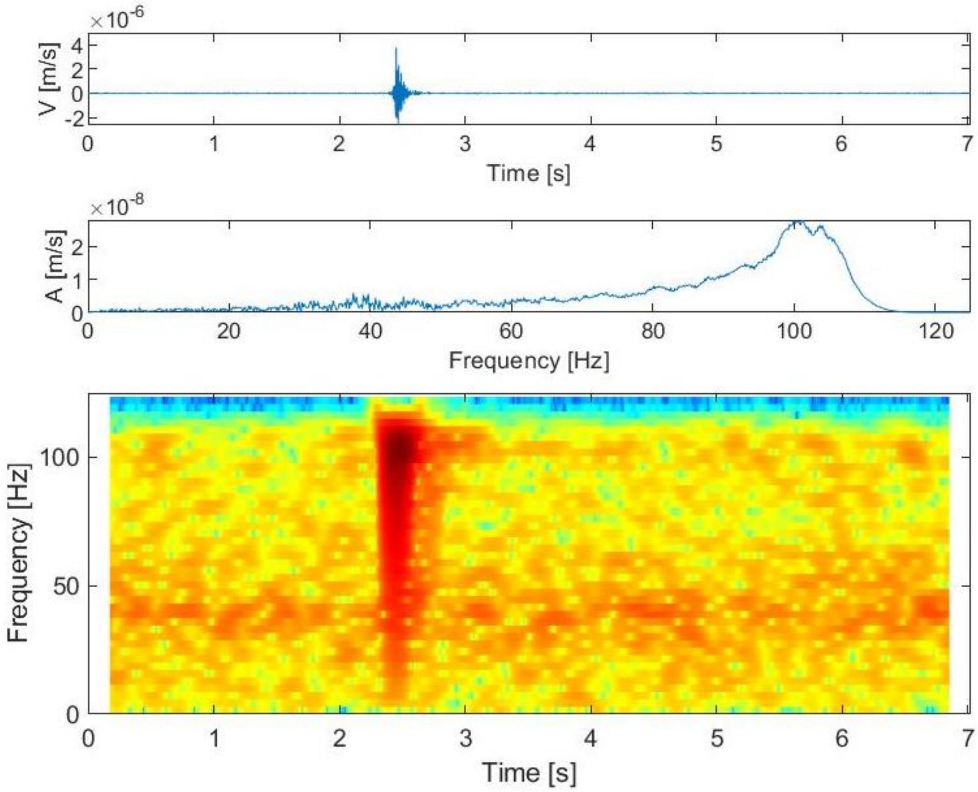

Figure 34: Example of Rock fracturing.

8) Conclusion

In this work, the goal is to estimate if the climate variables, in term of precipitation or temperature variation, are responsible for the creation of a changes along and inside the slope at the top of the Bossea Cave. Furthermore, studying climate change inside a cave or the surrounding area is something special, much more difficult than analyzing other aspects or other cases relating to climate change, as they require a more precise and in-depth study of many components inside, interior of the cave ecosystem.

Obviously during the work, some problems and difficulties have been encountered. In the first part, namely that of geomatics, the use of an open software such as OpenDroneMap, led to problems:

- the first was not being able to work on all the images together, but dividing them into different parts was not easy;
- the second was to have to combine them and verify that what was obtained was correct and of excellent quality.

In synthesis, working with a non-open software it is possible to obtain better results and to be able to work with a large number of images as in this case. On the part of geophysics, however, the part on the final deductions and the interpretation of the graphs, with little experience, was not immediate.

At the same time, other aspects such as retrieving meteorological data or downloading data from stations and processing them were faster and easier.

In conclusion it was an interesting job, also because working with different software and then changing the approach and the interface every time was stimulating.

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