POLITECNICO DI TORINO

Master's degree in Environmental and Land Engineering

Geo-Engineering

Securing and monitoring of tourist routes
The case of Chianocco Gorge

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Abstract

The allure of mountainous regions for tourism is undeniable, yet the scenic splendour and natural abundance come hand in hand with geological hazards, such as landslides, posing threats to the safety of tourist routes. Safeguarding these routes is imperative for maintaining the usability of mountain areas and ensuring safe and sustainable tourism. The thesis aims to identify solutions that secure tourist routes while preserving the visual integrity of the landscape.

To show the objective of this thesis, the specific case of Chianocco Gorge is analysed, nestled within a Natural Reserve near Turin, a coveted destination for outdoor enthusiasts, temporarily closed since March 2020 due to identified boulder movements.

In order to facilitate comprehension of the issue, a theoretical foundation on gorge formation and various types of rock failure is initially presented. Following the geomorphological framing of the site, the next step involves estimating the volumes of unstable rock—an indispensable dataset for designing effective mitigation measures.

The proposed solutions balance the imperative to enhance security with the necessity to preserve the site's aesthetic appeal, striving to minimize visual impact. Nevertheless, visitors to such locations must be cognizant that achieving a zero-risk environment is unattainable, emphasizing the perpetual need for caution. These objectives can be attained through the implementation of continuous monitoring and alarm systems as preventive measures.

Introduction

The attractiveness of mountain areas for tourism is undeniable, however, scenic beauty and natural wealth coexist with a number of geological hazards, including landslides, that can compromise the safety of tourist routes. The need to ensure the safety of such routes becomes crucial to preserve the usability of mountain areas and ensure a safe and sustainable tourism experience.

This thesis focuses on a specific case study, namely Chianocco Gorge, which is situated within a Natural Reserve near Turin. This gorge is revered as a prime destination for outdoor enthusiasts and mountain aficionados. Its allure is further heightened by the abundance of hiking trails and via ferrata routes that crisscross its rugged terrain.

Nevertheless, subsequent to inspections carried out by a mountain guide, discernible revealed noticeable movements of certain monitored boulders positioned at the Gorge's entrance. So, as a precautionary measure, the area was temporarily closed since March 2020.

Hence, this thesis offers a comprehensive exploration of securing tourist routes, specifically delving into the case study of the Chianocco Gorge. The primary aim is to identify solutions that safeguard these routes without compromising the visual integrity of the landscape.

The first chapter of this thesis focuses on understanding the natural dynamics that characterize gorge formation and the different types of rock failure. It also delves into further examples similar to the Chianocco Gorge case, shedding light on demanding tourist trails susceptible to landslide movements. Specifically, the exploration focuses on a gorge in French territory and the ongoing transformation of an old military trail in hilly terrain, catering to both sports enthusiasts and tourists.

The second chapter explores the specific case of Chianocco Gorge, initiating with a geographic framing and followed by a geological and geomorphological one. Furthermore, it delves into risk assessment, providing a comprehensive overview, elucidating the terminology and the various steps in a risk analysis.

Then, the third chapter conducts an in-depth analysis of the risks associated with the Chianocco Gorge case, that is the ones related to the unstable rocks. It meticulously examines various methodologies for estimating the volume of these blocks.

It highlights the necessity for access to the study area, prioritizing the needs of tourists as the primary element at risk. This section also explores the critical concepts of land use, land cover, and their connection to susceptibility, particularly in the context of tourism. Lastly, the chapter delves into vulnerability in risk assessment, scrutinizing the steps involved in forming vulnerability curves.

The fourth chapter discusses risk management and mitigation in landslide-prone areas. Various types of interventions are examined, including those proposed for the case of Chianocco. This chapter provides an overview of strategies and measures taken to ensure the safety of tourist routes in areas of high landslide risk.

The fifth chapter addresses the importance of monitoring and warning systems to prevent dangerous situations. The key components and aspects of a monitoring system are analysed, with a focus on the systems proposed for Chianocco Gorge case study, to ensure timely identification and response to potential hazards.

It is underscored that monitoring is not classified as an active form of mitigation measure in a physical sense; that is, it does not eliminate the risks. Instead, it functions as a measure to manage and, in some instances, consistently control the risks. Essentially, monitoring systems are intricately linked to the concept of the "recurrence factor" of a potential hazardous event.

To conclude, the concluding chapter encapsulates the key findings and reflections derived from this thesis.

1. Presentation

The initial chapter of this thesis focus on grasping fundamental theoretical basis linked to the Chianocco case study, like the natural dynamics linked to the gorge formation and the different modes of rock failure.

So, it deals with the **erosive action** of water, tectonic processes and glacial activity, all phenomena that contribute to the creation of these grooves defined gorges.

The second section conducts an examination of diverse **forms of failure** (plane, wedge, toppling, rockfall) and analyses the factors that could create instability in the slope, highlighting the difference between driving forces and resistance forces.

Moreover, emphasis is placed on the identification of **discontinuities**, essential for locating potential sliding surfaces and consequently evaluating blocks at risk of falling.

Concluding this chapter, it presents additional examples analogous to the case under consideration of Chianocco Gorge, focusing on **rugged tourist trails** susceptible to landslide movements. Specifically, it details the case of a gorge in French territory and the ongoing utilization of an old military trail in hilly terrain as a route for sports enthusiasts and tourists.

1.1 Gorges formation

The gorges (an example in *figure 1*) are complex geomorphological formations, constituting one of the most obvious results of the relentless erosive work done by watercourses over geological time.

The **action of rivers**, fed by water from meteoric precipitation or/and snowmelt, sculpt gorges as they traverse the terrain, transporting rocks and sediment along their course. Over time, the relentless movement of water and the abrasive action of these geological materials it carries gradually carve out a profound chasm in the landscape, revealing numerous strata of rock (Libal, Angela 2023).

This plays an important role in the gorges' formation and, specifically, among the key processes involved in river action it is possible to recognize:

- *hydraulic erosion*, which acts through the mechanical pressure exerted by stream flow on rock.
- *abrasive erosion*, due to the transport of sediments that rub and smooth the surface of the surrounding rocks.
- *corrosive erosion*, resulting from the acidity of water.

Anyway, they are also evidence of the dynamism and constant evolution of the natural landscape. In fact, although erosion from water bodies remains the main responsible factor, the process of gorge formation is expedited by the interaction of several geological processes, including **tectonic processes** such as vertical uplift and cave collapses (Libal, Angela 2023).

For instance, during the process of geologic uplift, certain sections of streams or rivers, as well as the surrounding land, can become elevated, so they often give rise to waterfalls. As time progresses, the force of the waterfall gradually erodes the softer rock layers beneath it, ultimately leading to the collapse of the original riverbed and the formation of a gorge (Rutledge et al., 2023).

Finally, gorges can also be the product of **glacial activity**, where the movement and melting of glaciers play a significant role. Indeed, glaciers are able to carve wide valleys into the earth's surface, leading with melting to the formation of gorges (Rutledge et al., 2023).

Figure 1 – Example of a gorge, the Royal Gorge, in Colorado (Melanie Saberian, National Geographic).

1.2 Types of rock slope failures

The stability of rock formations, especially in the case of high altitudes, presents a significant geological challenge in the development of projects within mountainous regions (Dong et al., 2021).
These are often areas heavily frequented by tourists for various activities, which is why it is even more important to analyse the risk and secure possible unsafe parts.

The **stability** is influenced by a multitude of **factors**, including geological characteristics, mechanical properties of the rock mass, parameters related to joints in the rock, slope configuration and groundwater conditions (Dong et al., 2021).

Among these variables some acts as **driving** forces and others as **resistance** forces, and the relationship between these two types of forces affects the stability of the rock slope (Raghuvanshi, 2019).

1.2.1 Identification of discontinuities

Speaking of **discontinuities** and, it is necessary to open a parenthesis on the identification of the discontinuities and thus on potential sliding surfaces, in the case of **high-steep slopes**.

Indeed, as cited in the article by Wang et al. (2022), high-steep slopes can pose significant **challenges** for traditional methods of obtaining discontinuity data and identifying potential rockfalls.

The *sample window method* (**SWM**) and other similar techniques may become impractical or unsafe in such terrain. In these situations, alternative approaches and technologies are often necessary to assess and mitigate the risk of rockfalls.

With the advancement of *unmanned aerial vehicle* (**UAV**) technology, non-contact photogrammetry became a viable method for discontinuity identification. Nevertheless, a notable gap remains in the availability of pragmatic solutions for rockfall identification encompassing field investigations (Wang et al., 2022).

As a result, it's essential to combine different methods and technologies in order to collect more information and so to create a comprehensive understanding of the rockfall hazards on high-steep slopes. Safety is a paramount concern, so avoiding direct access to hazardous areas whenever possible is crucial, and utilizing remote methods and monitoring systems is often the safest approach.

Anyway, this chapter draws attention to the different types of failure that can generally affect these slopes.

1.2.2 Plane failure

The occurrence of this kind of slope failure is highly recurrent, particularly in sedimentary rock formations.

The necessary condition for plane failure to potentially be triggered is when a structural discontinuity (like fault, bedding plane, joint set...) is inclined towards the valley with an angle less than the slope angle but, at the same time, greater than the friction angle of the discontinuity surface (Tang et al., 2016, Kovari and Fritz, 1984).

Another requirement is the presence of a **tension crack** in the upper part of the slope (*figure 2*) (Raghuvanshi, 2019).

It follows that monitoring and resolution of these tension cracks are essential to assessing slope stability and mitigating potential landslide or slope hazards, making them a critical consideration in slope management and safety protocols.

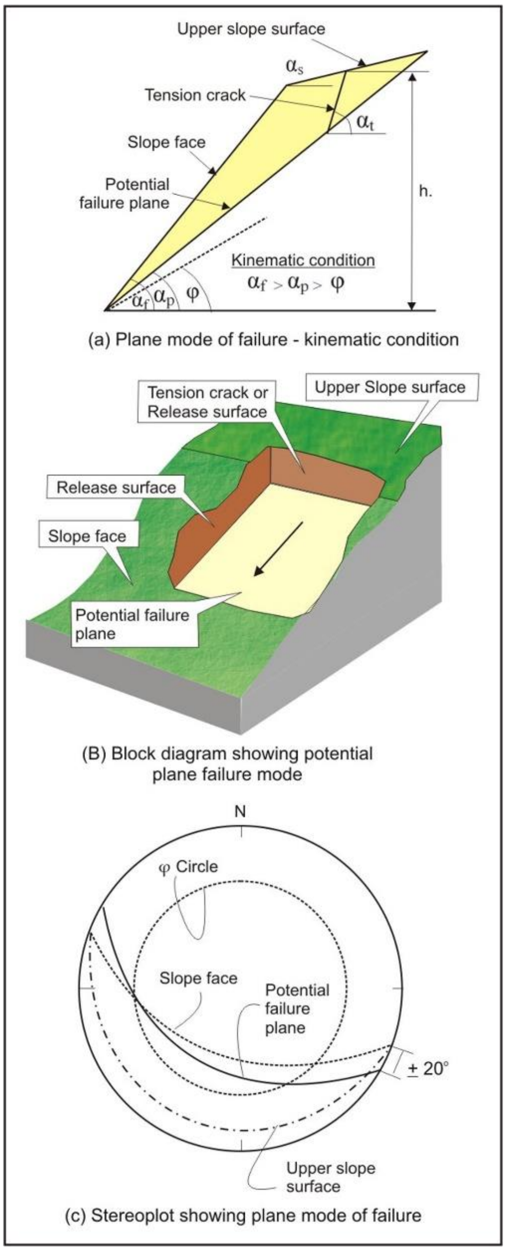

Figure 2 - Potential plane mode of failure (ScienceDirect, Raghuvanshi, 2019).

1.2.3 Wedge failure

The most common type of failure in slopes featuring extensively jointed rock formations is the wedge one.

The stability of these slopes is heavily influenced by the orientation of the rock mass's joints, which is determined by how these joints align with the slope's orientation (Mantrala et al., 2022).

Wedge failures are characterized by a failure mass determined by the presence of **two sets of discontinuities** intersecting each other at an angle away from the slope's surface. The condition for this breaking mechanism to occur is that the dip of the intersection's line must be greater than the friction angle and smaller than the dip of the slope face (*figure 3*) (Tripathi, 2020).

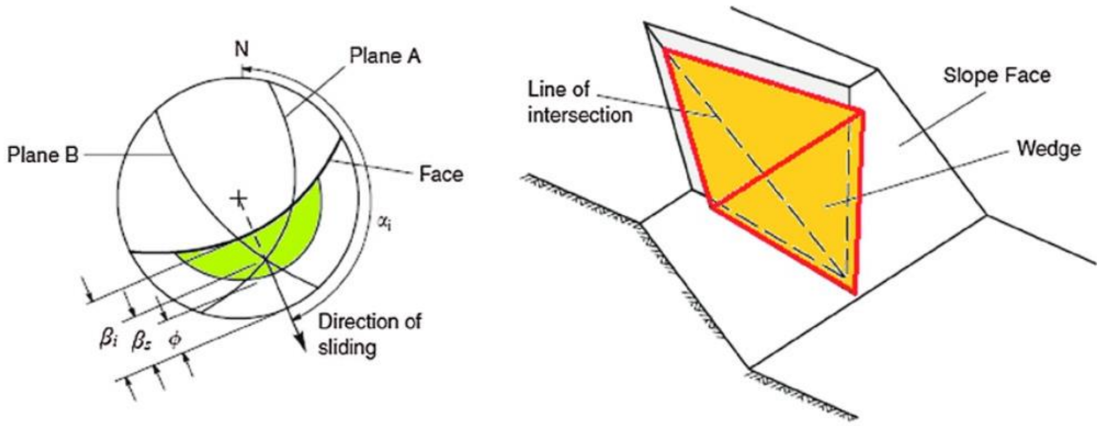

Figure 3 - Condition for wedge failure: stereography projection and view of a wedge failure (Rusydy et al. 2019).

1.2.4 Toppling failure

As described by Norman and Duncan (1996), toppling failures pertain to the instability of rock formations characterized by **set of parallel slabs** or columns steeply oriented against the slope surface (*figures 4, 5, 6*).

The necessary condition for the occurrence of this phenomenon is linked to the center of gravity of the rock column, that must be outside the dimension of its base. When a toppling failure occurs, the rock slab undergoes **rotational** movement around a relatively stationary point, that is typically located at or near the slope toe, and simultaneously there is an interlayer slippage.

The rock mass acts as if it comprises a sequence of overlaid inclined cantilever rock columns, each with the potential for flexural toppling failure (Majidi and Amini, 2011).

In *figures 4* and *6* are showed the different forms of toppling failures existing, such as flexural, block and block-flexure toppling. The flexural one involves interlayer slip, enabling column to bend in flexure, while the block type takes place when two sets of discontinuities are present (Pereira et al., 2013).

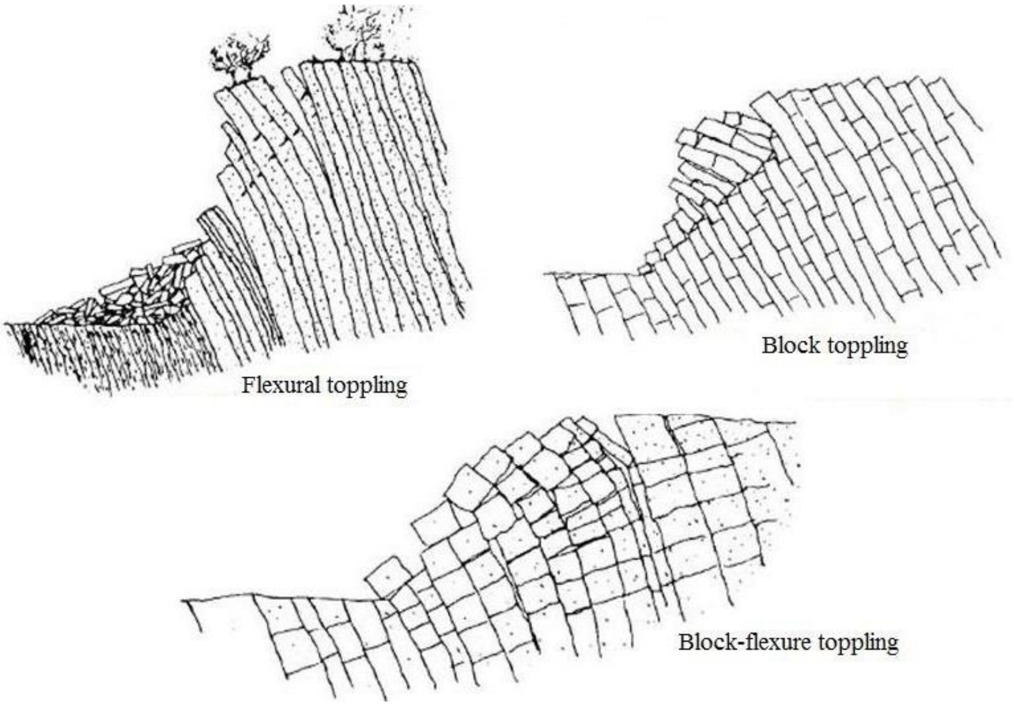

Figure 4 - Types of toppling (Goodman and Bray, 1976).

Figure 5 - Example with slabs are clearly visible.

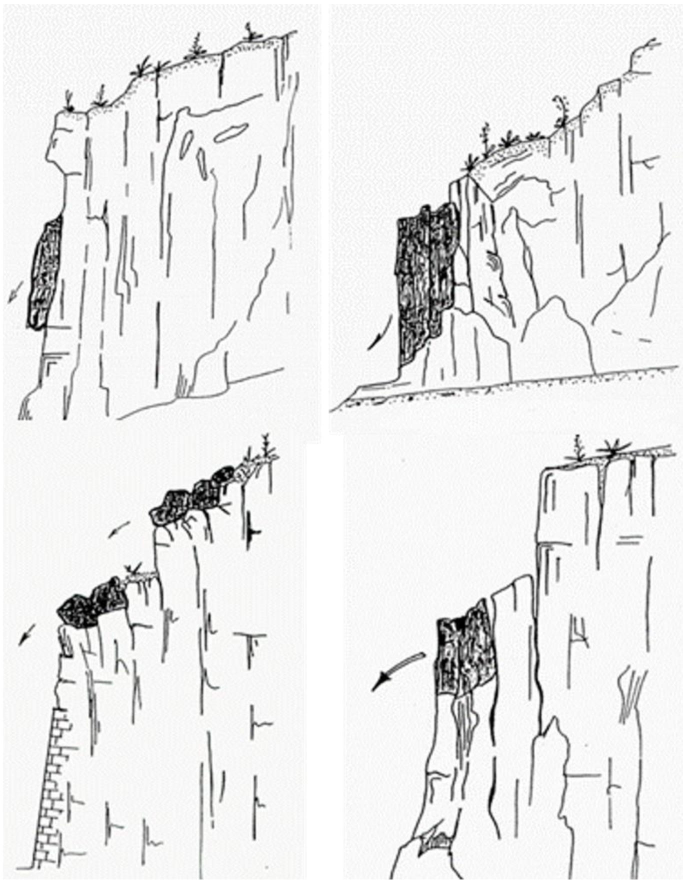

Figure 6 - Different types of movement in presence of parallel slabs.

1.2.5 Rockfall failure

Rockfall is characterized as "*a fragment of rock that becomes dislodged through sliding, toppling, or falling from a vertical or subvertical cliff. Subsequently, it descends by either bouncing and flying along parabolic trajectories or rolling on talus or debris slopes*" (Varnes, 1978; quoted by Ilinca, 2009).

So, rockfalls often happen on steep slopes when rock blocks detach from natural joints and fractures in the rock without smoothly sliding on the curved surface. In cases where the rock slopes are **heavily fractured** and have experienced weathering, the risk of slope failure increases (Tripathi, 2020).

These occurrences are closely associated with both climatic factors and human activities that contribute to slope instability (Ilinca, 2009).

According to Hoek (2007), "*rockfalls are typically* ***triggered by*** *climatic or biological events that induce alterations in the forces acting on a rock*".

These include elements like the increase of pore pressure from rainfall infiltration, the erosion of surrounding material during heavy rainstorms, freeze-thaw processes in cold climates, chemical degradation or weathering of the rock, as well as the root growth or exertion of force by roots in high winds (Ilinca, 2009).

Regarding the **climatic factors** that can induce this mode of failure in rock, it is important to note that we are not only referring to heavy rainfall, or phenomena associated with bad weather in general.

Contrary to common assumptions, as highlighted in S. Zielinski's (2016) article, approximately 15 percent of rockfall incidents take place during the peak **heat** of the year and the hottest periods of the day.

As Stock and Collins assert (2016), the intense heat during the day can exert sufficient stress to push a rock slab to its breaking limit. In detail, as the morning sun ascended and the air temperature increased, Stock and Collins discovered that the rock would absorb heat, causing it to expand away from the cliff. Conversely, during the night when the temperature dropped, the rock would cool and contract back toward the underlying cliff. "*Every day, we observed this rhythmic movement*", they noted.

Finally, as pointed out by Valentin Gischig of the Swiss Competence Center, "*Possibly, as the* ***climate warms*** *in the coming decades, thermally induced rockfalls may become even more important to hazard assessment and cliff erosion*".

As with many landslide phenomena, rockfall can be divided into the three zones in which the phenomenon manifests itself: **initiation** zone, propagation (**run-out**) zone and **arrest** zone. However, the subdivision for rockfall is more intricate than for other instability phenomena. This complexity stems from the fact that the boundaries between initiation, propagation and arrest are not clearly defined. During collapse, there is a continuous overlapping of areas of initiation and areas of partial arrest of rock volumes, with the possibility of resumption of movement as a result of impacts and increases in slopes (Giani, 1997).

It is important to consider that, depending on the **surface** on which these detached boulders roll, different **behaviours** can occur. The most hazardous situations involve smooth faces of hard unweathered rock since they are not able to decrease the movement of the rockfall. Conversely, when surfaces are layered with material like scree, or gravel, they can dissipate a substantial portion of the energy from falling rocks and often bring the rocks to a complete standstill. This behaviour of the surface can be expressed through the ***coefficient of restitution*** **(COR)**, high in the case of clean hard rock and low in the other one (Hoek, 2000).

This coefficient is a measure of how much **kinetic energy** is retained or lost during collisions between rockfall masses and surfaces. As it represents the dissipation of kinetic energy resulting from a collision, determining its magnitude requires knowledge of the **velocities** both **before** and **after** the impact. In particular, it will be expressed by the ratio of the velocity of the block after impact to the velocity after impact.

The coefficient of restitution stands out as a paramount parameter in the analysis of rockfall hazard, and it can be determined through either field tests or laboratory experiments (Tang et al., 2021).

The objective of these **tests** is to determine in situ velocities, often conducted through rockfall tests. Nevertheless, these tests can be prohibitively expensive and intricate. As an alternative, the literature often resorts to utilizing **tables** or employing **back analysis**. The latter involves leveraging analogous phenomena that occurred at the same location in the past, adjusting them on a case-by-case basis by varying specific parameters. These approaches prove valuable in instances where conducting direct tests is impractical.

Rockfalls can vary in scale from minor incidents to more substantial ones (example in *figures 7, 8*), that pose risks to people's safety and have the potential to inflict **damage** on infrastructure. So, rockfalls often lead to the destruction of roads and railways, resulting in substantial financial losses. Even in instances where they don't cause direct damage to the infrastructure, financial losses are incurred due to periodic traffic interruptions, necessitating expenditures to clear the way (Ilinca, 2009).

Rockfall deposits are widespread in numerous mountainous and hilly regions across the globe (Varnes, 1978; Evans and Hungr, 1993; Wieczorek, 2002; Dorren, 2003; Guzzetti et al., 2003).

They offer valuable data for **evaluating future rockfall hazards** (Porter and Orombelli, 1981; Keefer, 1984; Dussauge-Peisser et al., 2002; Copons and Vilaplana, 2008; Wieczorek et al., 2008; Stock et al., 2014; quoted by Borella et al., 2019).

This type of rock failure precisely embodies the hazard identified in the Chianocco Gorge case study. Next chapters will provide a more in-depth exploration of this case study, elucidating the rockfall risk **assessment** and outlining potential measures for risk **mitigation**.

For the design of remedial measures and the mitigation of rockfall phenomena, simulation programs predominantly rely on a probabilistic lumped-mass analysis model (Asteriou et al., 2012).

Figure 7 - Image depicting the Moira region following a rockfall incident (Kakavas et al., 2023).

Figure 8 - An example of rockfall failure in Yosemite National Park (Tom Evans, 2010; quoted by Zielinski, 2016).

1.3 Rugged mountain tourist routes

Before delving into the case study presented in this thesis, it is important to lay the groundwork with a chapter dedicated to the general case history of comparable instances. It is, indeed, noteworthy that the existence of challenging tourist routes in mountainous regions is not an uncommon phenomenon.

The common thread among these instances of tourist routes in mountainous areas is the evident necessity to ensure security without compromising the intrinsic natural beauty, which proves to be the primary challenge.

The cases featured in this chapter revolve around the "Gorge de la Diosaz" in Le Bouchet, Auvergne-Rhône-Alpes (France), near Sallanches, and the "Colle della Vecchia" in the upper Susa Valley (Italy).

As depicted in *figure 9*, the first example bears a striking resemblance to the case examined in this thesis. The "**Gorge de la Diosaz**", situated in French territory, entails a narrow gorge where a wooden handrail was installed to facilitate safer passage for tourists along the trail. Wooden handrails represent a prevalent form of support in these locations, owing to their suitability for the landscape, ensuring minimal visual impact.

In *figure 10*, a section featuring an anchored mesh system is visible, serving to safeguard the trail from potential rockfall.

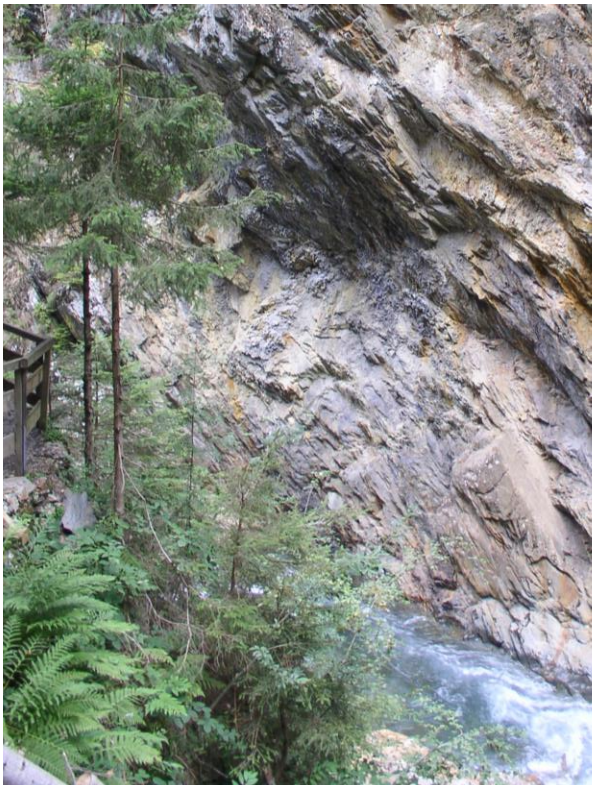

Figure 9 – On the left, path with handrail near the Gorge de la Diosaz (Oggeri C.).

Figure 10 - System of anchored mesh visible on the right, above the path (Oggeri C.).

Another compelling case involves an **old military road** located in **Colle della Vecchia**, very close to France, in the upper part of the Susa Valley (*figures 11, 12*). This road, repurposed as a tourist route, is suitable for pedestrian hikers, mountain bikers, and e-bike riders, and attendance saw a significant rise in recent times. Unfortunately, this trail is marked by persistent landslides, rendering it impracticable.

For this reason, precautionary measures were implemented at this location, with transit being suspended since May 2020 due to a landslide occurring in a section below. Subsequent instances of additional cracks and heightened instability have further extended the closure period.

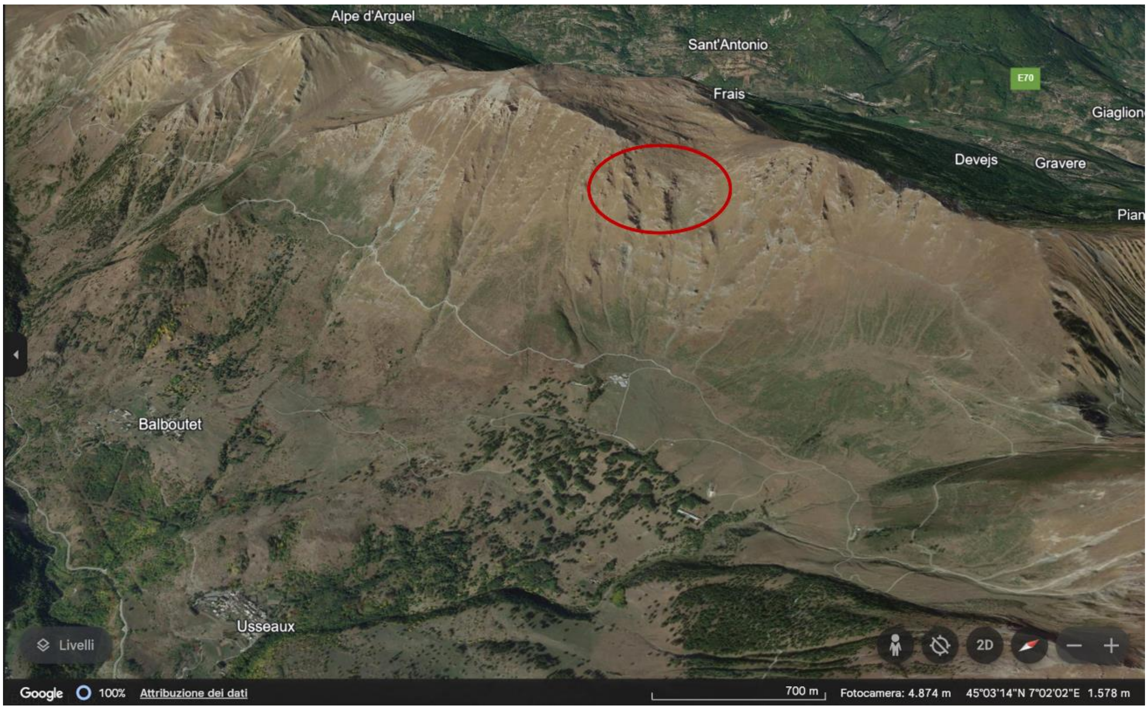

Figure 11 - Marked with a red circle military trail of the Colle della Vecchia (from Google Earth).

Figure 12 - Military trail through the hills (from Google Earth).

Figure 13 showcases excerpts from historical military manuals employed in the construction of these routes originally designed for military garrisons. Replicating the exact features from that period may be challenging, where the proposed solution aligns well with the naturalistic landscape.

Indeed, the construction involves the use of reinforced concrete with tie rods, concealed beneath a dry-stone wall to ensure a visually harmonious integration with the natural landscape. Additionally, a modest foundation and backfill are incorporated using local debris material.

Addressing instability is currently achievable through techniques that extend beyond mere “art works”, employing consolidation and reinforcement interventions to meet technical standards and ensure adequate safety factors. Localized interventions may also consider straightforward repairs involving the reconstruction of dry-stone walls.

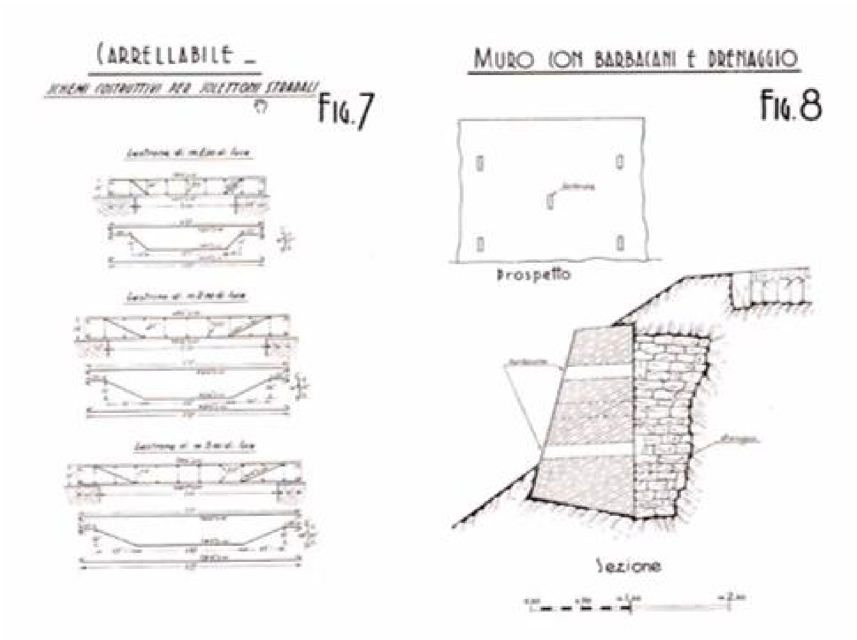

Figure 13 - Old military manuals for trail construction (courtesy of Casale M.).

The subsequent figures present various details of the site. *Figures 14, 15, 16, 17* highlight the presence of different big bags strategically placed to deter cyclists from progressing into areas where the route poses heightened risks. In *figure 16*, a bird's-eye view of the trail during winter is depicted. *Figure 17* illustrates a detail of the void created by the collapsed section of the wall.

Figure 14 - Big bags to impede the passage (courtesy of Casale M.).

Figure 15 - Top right, closer representation of the trail (courtesy of Casale M.).

Figure 16 - Path with big bags in winter season (courtesy of Casale M.).

Figure 17 - Detail of big bags. In this image, the collapsed section of the wall is clearly visible (courtesy of Casale M.).

2. The case of “Chianocco Gorge”

2.1 Introduction

This chapter delves into the specific case of Chianocco Gorge. It begins with the geographical, geological and geomorphological context of the site.

The exploration aims to provide a comprehensive understanding of the unique attributes that define the landscape of Chianocco Gorge, setting the stage for a thorough investigation into the risks assessment and the subsequent implementation of effective mitigation measures, addressed in subsequent chapters.

Geographically, the Chianocco Reserve is integral to a designated S*ite of Community Interest*, known as the “Susa Valley Xerothermic Oases”.

From a **geological** and **geomorphological** standpoint, there is an initial overview with a lithological map of the Susa Valley, mainly comprised of limestone schists. Notably, the Chianocco Gorge area is distinguished by limestone (*figure 18*) cliffs, gullies, and erosion pyramids. Meanwhile, in the Foresto region, the renowned “Marble of Foresto” stands out, widely employed in architectural applications.
This chapter also includes a section dedicated to the different structural units present in this area, highlighting the specific inclusion of the case study within the **Dora Maira** unit, characterized by its continental nature. Within this unit, a distinct **Paleozoic**-type basement and a **Mesozoic** cover can be identified.

The subsequent section addresses **risk assessment** in a general manner, elucidating essential terminology and the different stages, while the next chapter will delve into the specifics of the Chianocco Gorge, distinguished by the presence of potentially unstable blocks.

Figure 18 - Example of limestone stone.

2.2 Geographical framing

The area considered in this work is a protected natural area in the province of Turin, in Piedmont. It is known as "**Chianocco Gorge Natural Reserve**" and covers about 40 hectares with altitudes between 550 and 950 m.

The Chianocco Reserve, designated in 1980, forms an integral component of a SCI (*Site of Community Interest*) called the "Susa Valley xerothermic oases", encompassing both the Chianocco and Foresto Gorges. In particular, the **Susa Valley xerothermic oases**, managed by the *Cottian Alps Protected Areas Management Authority*, are designated as *Special Areas of Conservation* (SACs), for which the regional authorities developed appropriate Conservation Measures and received official designation through ministerial decree, in collaboration with the respective regional administration (from Rete Natura Piemonte, 2009).

The xerothermic oases, that involve the municipalities of Bussoleno (49%), Chianocco (9%), Mompantero (35%) and Susa (7%), cover an area of 1410 ha (*figure 19*) on the hydrographic left side of the central sector of the Susa Valley and the SIC boundaries reach an elevation of 1,600 m at Mount Ciarmetta and the Corbassera Ridge, in Bussoleno.

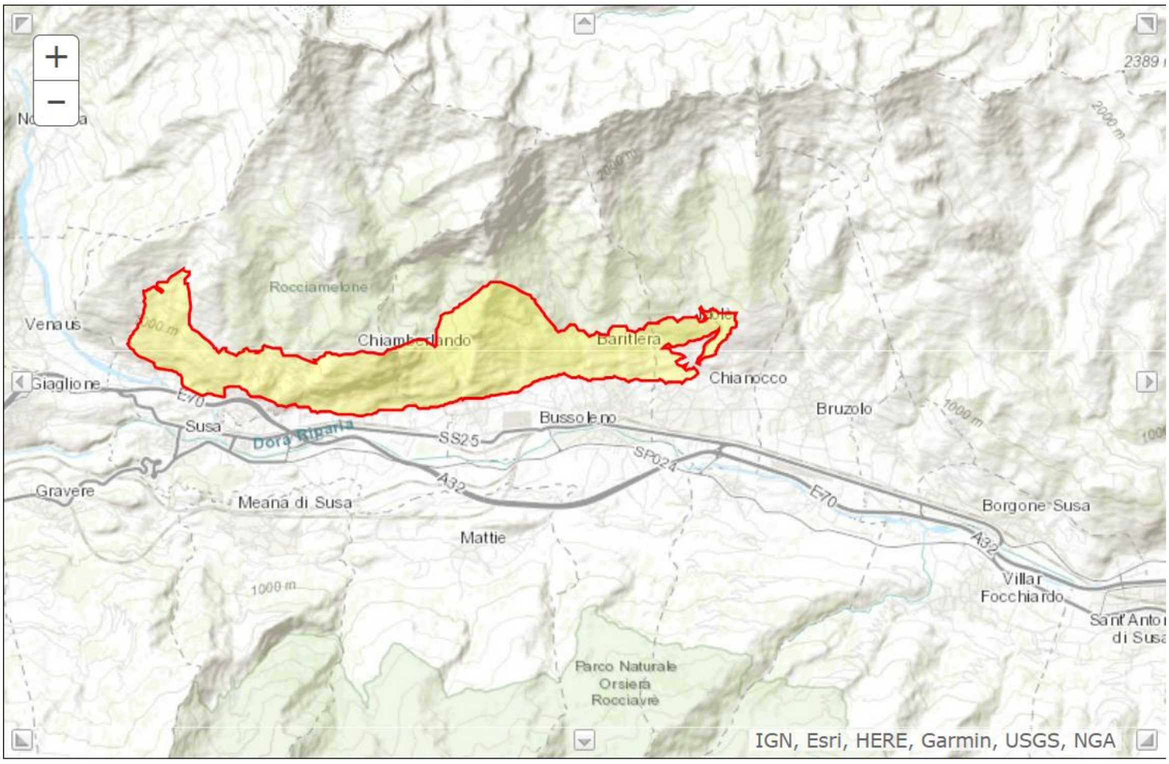

Figure 19 - Geographical boundaries of Susa Valley xerothermic oases (Natura 2000).

2.3 Geological and geomorphological framing

Geology plays a crucial role in hazard assessment, as it impacts the intensity of events by virtue of lithological complexity and the existence of joint sets (Ilinca, 2009).

Prior to delving into the specifics of geological eras, it is pertinent to provide an overview of the lithological map of the Susa Valley and to offer a concise introduction to the most distinctive stones found in the region.

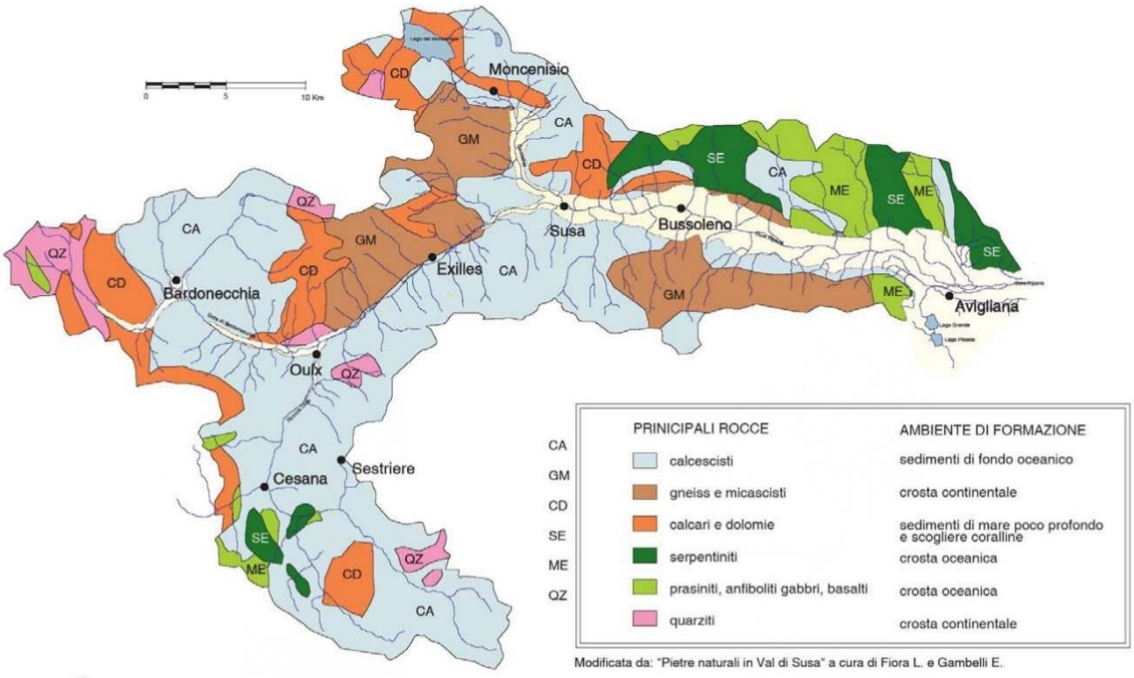

Figure 20 - Lithological map of the Susa Valley (Pellegrino, from "I Meridiani").

What can be seen at a glance from this map in *figure 20* is that **calcschists** are the rock type with the greatest extent in the Susa Valley, followed by **gneisses** and **micascists** (in brown). The north-eastern zone is characterized by serpentines, prasinites, gabbro amphibolites, and basalts (in green). Each zone has its own peculiarity that distinguishes it from the others, for example, limestone rocks and dolomites (in orange) meet between Bussoleno and Susa.

In particular, **Chianocco** area is characterized by **limestone cliffs**, **gullies** and **erosion pyramids**.

In the Foresto area, on the other hand, there is the famous "**Foresto marble**", whose architectural and ornamental use can be seen in the historical works of nearby Susa. The source of the rock in Chianocco and Foresto is the same; nevertheless, the accessory minerals differ, occasionally resulting in various hues that span from white to light gray, occasionally exhibiting stripes. Chianocco's stone exhibits an ivory-white hue, leaning towards ochre shades, and is extracted in substantial blocks with a thickness reaching 10-12 meters. This characteristic enables its extensive application for column shafts or large architectural elements (Nemo, 2023).

Bussoleno was also a protagonist in mining in the past; in fact, it is still possible to find evidence of numerous quarries, from gneiss to “green” marble.

In Condove, one can observe the contact between continental rocks of paleo-African origin (gneiss) and the rocks from the prehistoric ocean (calcschists and greenstones).

Approximately 13,000 years following the last glaciation, Avigliana reveals a distinct glacial imprint: moraine hills adorned with concentric ridges, glacial lakes, erratic boulders, and rocks exhibiting smooth, striated surfaces.

Geomorphologically, there are several noteworthy features. First, the area under consideration has **limestone rock** walls of **coral origin** along the gorges carved by the erosive activity of the tributaries of the Dora Riparia. In particular, the walls of Chianocco Gorge were carved over thousands of years by the Prebèc tributary of the Dora Riparia.

There are also **moraine deposits of glaciers** (dating back to the end of the last glaciation) which, due to their easy erodibility, caused the formation of steep slope erosions phenomena called **gullies** and, in some areas just above the gorge (Margritt, Pianfé Alp, Molé Alp) gave rise to **earth pyramids**.

Thanks to the illustrative notes (Cadoppi et al., 2002) on Sheet No 154 “Susa” of the **Geological Map of Italy** very detailed geomorphological information on the area of interest could be obtained. They provide extensive geographical and morphological data, divided into geological eras, such as pre-Quaternary related to the basement unit and Quaternary related to the overlying unit. This Geological Map Sheet No. 154 (1:50,000 scale) encompasses the lower Susa Valley, a segment of the Chisone Valley, the southern part of the Cenischia Valley, the upper reaches of the Sangone Valley, and the Sangonetto Valley. Additionally, it also covers part of the area between the Susa Valley and the Stura di Viù Valley.

2.3.1 Pre-Quaternary

The pre-Quaternary geological period can be analysed by identifying two main **structural domains**. The first includes Continental Margin units that are characterized by a crystalline basement (**Ambin Unit** and **Dora-Maira Unit**), underlain by their respective overlying strata. The other structural domain includes Oceanic and Pit units, with Limestone and Ophiolitic Units.

Multiple structural units were identified within these domains, each defined by unique lithological compositions and exhibiting distinctive mineralogical, petrographic, and structural attributes.

In the following *figure 21a* it is showed the geological map of the Western Alps (Fusetti et al., 2012; quoted by Borghi et al., 2016) in which oceanic and continental units can be distinguished. Specifically, the area whose morphology will be analysed, involves the Piedmont Zone of the Oceanic units and the Upper Penninic Units, part of the Continental units.

The red rectangle highlights the area of the Dora-Maira subunit, where Chianocco Gorge is located. Therefore, it is necessary to include a more detailed image related to this zone (*figure 21b*, Borghi et al., 2016) in which the various types of ornamental and building stone characteristic for each area are indicated in the legend.

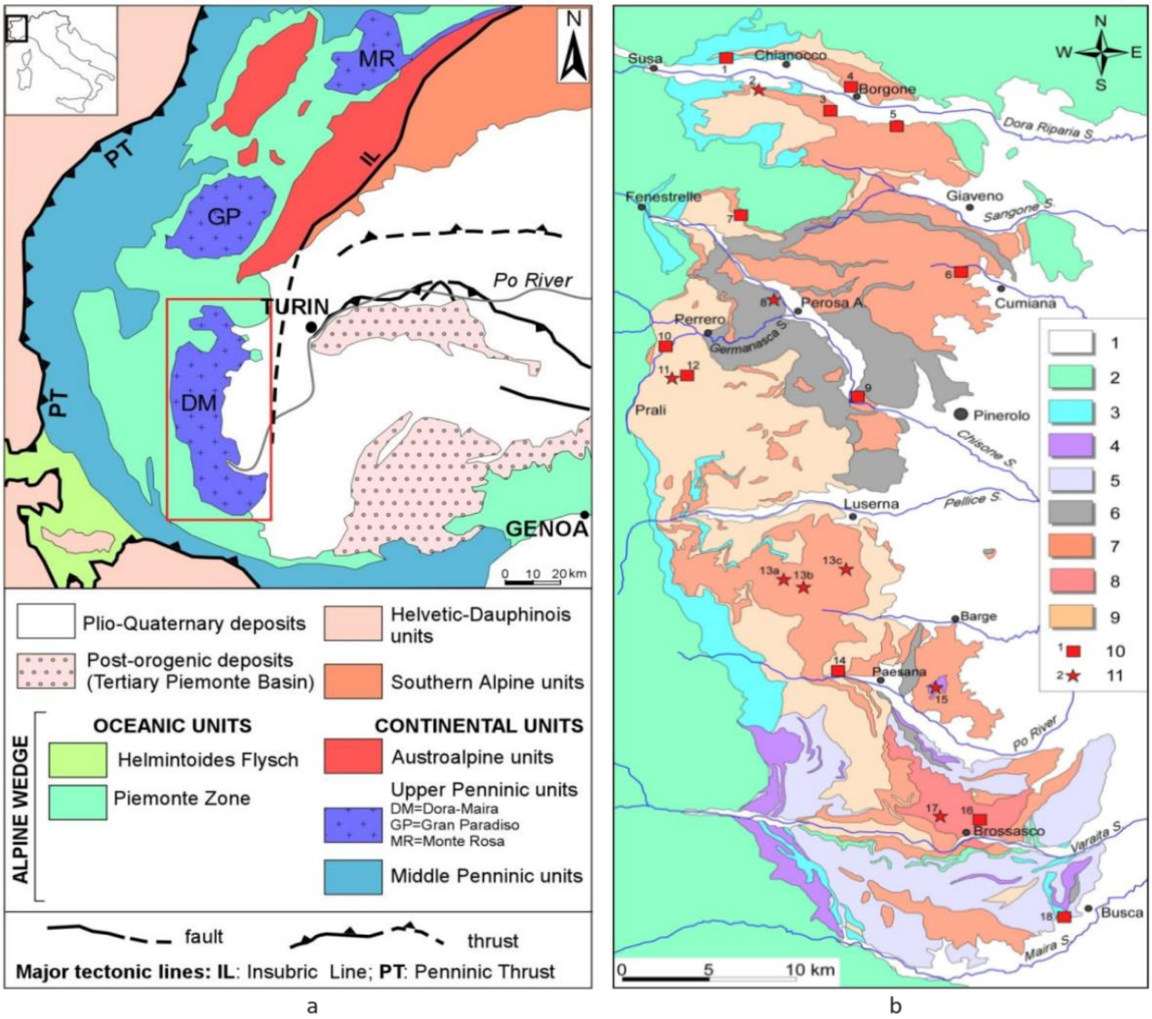

Figure 21 – a) Western Alps geological map; b) Dora-Mair Unit map with ornamental and building stones in the legend: 1) Quaternary deposits; 2) Piedmont ophiolite nappe; 3) Mesozoic cover; 4) impure quartzite; 5) fine-grained gneisses micaschists; 6) graphite-bearing micaschists; 7) metaintrusives; 8) orthogneisses and metagranitoids, coarse-grained garnet micaschists, pyrope-coesitequartzites, silicate marbles and metabasites; 9) polymetamorphic garnet-chloritoid micaschists, impure marbles, eclogite-facies; 10) historical quarries; 11) quarries active in the last decade (quoted by Borghi et al. 2016).

In addition, as pointed out in the illustrative notes of Sheet No 154 "Susa", it appears that the northern and southern sectors experienced distinct phases of Alpine tectono-metamorphic evolution.

Specifically, in the **northern** boundary, a high-pressure paragenesis (HP) was identified in metamorphic rocks such as metabasites, metapelites, and granitic millionites, suggesting the presence of an Eoalpine phase within the eclogitic facies (Bellion 1982, Borghi et al. 1985, quoted by Cadoppi et al., 2002), followed by others metamorphic evolutions.

In the **southern** part of the Massif, discoveries of quartzites, talc, kyanite, and phengite suggested ultra-high-pressure conditions (UHP, P>35 kbar). These ultra-high-pressure metamorphism led to the formation of the rare pyrope-coesite assemblage in whiteschists and the jadeite-coesite assemblage in granofels (*figure 22*).

Nonetheless, the internal morphological configuration of the Massif remains a subject of ongoing debate, with varying interpretations.

Figure 22 - Pyrope crystals (UHP rock) in Gilba Valley, Cuneo province (from mindat).

2.3.1.1 Dora – Maira Massif (Continental Margin Unit)

Chianocco Gorge falls within the structural domain of the Dora-Maira. The Dora-Maira geological formation is exposed in the central area of the Cottian Alps and is affiliated with the Penninic Domain within the Western Alps (as seen in the *figure 21*), specifically in the north-western region of Italy.

Owing to the intricate nature of the rock compositions and the metamorphic changes in texture, the Dora Maira Unit served as a longstanding source of decorative stones (like Luserna Stone, Bargiolina Quarzite, Chianocco marbles…). Even today, it continues to provide a local supply of materials used in both historical and modern construction projects (Borghi et al., 2016).

A **Paleozoic basement** can be identified in the Dora – Maira Massif unit, with a predominantly carbonate **Mesozoic cover**.

2.3.1.2 Pre-Triassic basement

The pre-Triassic basement consists of both a polymethamorphic complex (dating back to the Pre-Carboniferous era) and a monometamorphic sequence of micaschists, gneisses, and quartzites of the Pinerolese Graphitic Complex (related to the Carboniferous age).

The **polymetamorphic** complex is mainly composed of metapelites, metabasites, impure silicate marbles and orthogneisses (Cadoppi, 1996; quoted by Borghi et al., 2016).

The materials of this **monometamorphic** unit, are mostly composed of paraderivates of detrital origin, both fine-grained (metapelites) and coarse-grained (metaconglomerates) and are characterized by the presence of graphite. Specifically, the predominant rock type consists of predominantly graphitic micaschists while minute gneisses and metaconglomerates are present in more limited quantities.

Crinoid fossils were also discovered in the dolomites of the Chianocco region, within both native and para-autochthonous carbonate sequences of the overlying strata.

2.3.1.3 Mesozoic cover

The Mesozoic cover can be categorized into three main complexes, each distinguished by their structural placement and lithological characteristics: the Pavaglione complex, the Foresto – Chianocco – M. Molaras complex, and the Meana – M. Muretto complex.

The **Meana – M. Muretto Complex**, exclusively located on eastern side of the Susa Valley, primarily comprises metapelites ranging from calcescists to micaschists varieties, as well as serpentines, impure marbles, and leucocratic paragneiss. Additionally, dolomitic marbles are observable at the uppermost part.

The Mesozoic cover of the left slope consist of the metadolomies, impure marbles and calcschists complex, which represent the **Foresto – Chianocco – M. Molaras Complex**. In particular, the extent of this complex is enclosed between the Permo – Trias, consisting of impure quartzites, and the Upper Cretaceous, typically composed of marbled calcareous and impure marbles (Marthaler et al., 1986; quoted by Cadoppi et al., 2002).

Going into detail, in the sequence of marbled calcareous rocks, it is possible to identify *metadolomies*, which are white, monotonous, fine-grained, and poorly fractured rocks. With the same mesoscopic characteristics as this rock, there is also *dolomitic marble* (*figure 23*), which is distinguished by greater amounts of calcite.

Figure 23 - Dolomitic marble (from Atlante di petrografia UniTo).

Blue-grey marbles, with medium-fine-grained also outcrop in this Complex. It is possible, mineralogically speaking, to associate these marbles with carbonates and quartz and contain recrystallized calcite, the colour of which is darker than the matrix.

There is also the presence of *marbled calcescists with subordinate intercalations of phylladic calcescists*. This rock variety displays a greyish-brown hue and is distinguished by its medium-fine grain and foliated texture. A lithological affiliation can be established with phylladic calcschists, micaschists, and chloritoschists, while mineralogical affiliation is be linked to calcite, white mica, and quartz.

Finally, the **Pavaglione Complex** consists of quartzites, metadolomies and dolomitic marbles, calcschists and quartz-micaschists.

2.3.2 Quaternary cover

Two types of deposits can be distinguished in the Quaternary period, those arising from **glaciers** and those arising from **water currents**. Specifically, within the glacial deposits, we can distinguish materials originating from **three distinct glacial periods**. Among these, the deposits from the earliest glacial period are situated in close proximity to the valley's opening, whereas those from subsequent glacial events are more widely spread throughout the middle and upper reaches of the valley.

2.4 Risk assessment

"Risk assessment consists in determining whether or not the calculated risk is acceptable by the community, and to what extent" (Fell and Hartford, 1997; quoted by Frattini and Crosta, 2006).

Conducting a risk analysis and assessment can be a valuable support tool for land management authorities. This practice enables the **identification** of risk scenarios, **mitigation** strategies and the identification of the optimal solution. Taking into account the peculiarities of the landslide and the socio-economic conditions of the area, several intervention alternatives for risk reduction can be identified (Frattini and Crosta, 2006).

Nevertheless, despite advancements in hazard recognition, prediction, mitigation measures, and warning systems, there is a global surge in **landslide activity**. As reported by Dai et al. (2002), this upward trajectory is anticipated to persist throughout the 21st century, driven by the following **factors** (Schuster, 1996): urbanization, deforestation, climate change.

Risk assessment is carried out by different steps. First, the **identification** of the hazard. In the risk analysis, the elements exposed to risk are considered, as well as the potential direct impacts on human lives, buildings and infrastructure.

At the same time, it is fundamental to establish landslide risk **acceptability levels**, by including, in this process, the community exposed at risk through different surveys and analysis of socioeconomic data.

Then, it is necessary to study the **vulnerability** of the location, that is referred to the susceptibility to damage as a result of a hazardous event.

Risk assessment is followed by a risk **management** and **mitigation** study, in which solutions to reduce the probability of occurrence or to reduce the damages are proposed based on various factors, related to the case study.

2.4.1 Terminology

A parenthesis on the terminology used is necessary for the understanding of this topic. It is possible to state that the risk analysis requires the estimation of different values: the hazard (H), the vulnerability (V) and the value (W) of the elements at risk. Starting with this assertion, it becomes feasible to delve into a comprehensive exploration of key terms.

For the following definitions, inspiration was taken from a Power Point by Eng. Barbero (2011):

The **hazard (H)** is characterized as the likelihood (p) of an adverse event (F) transpiring within a specified time frame and a defined geographical region (Varnes et al., 1984).

$$H = p(F = x, y, z, t)$$

The **vulnerability (V)** is the extent of damage caused by a potentially hazardous event of a specific intensity on a particular element at risk and its value ranging from 0% (no loss) to 100% (total loss).

Concretely, the vulnerability represents the link between the intensity with which a given phenomenon occurs and its potential consequences. During preliminary studies, the vulnerability is usually set initially at a conservative value of 1, assuming complete destruction of an element involved in a landslide event (Brogini, 2010).

The **elements at risk** involve the population, the properties, the economic activities, the assets, and the public services, that are exposed to risks in a given area. Limited research was conducted thus far on the repercussions of landslides on the natural environment and ecological systems.

The environmental consequences induced by landslides encompass alterations in agricultural practices, modifications in river morphology, and disruptions to natural ecosystems (Nakamura et al., 2000).

"Other effects included sedimentation in river channels and flash floods due to breaching of landslide dams" (Tien et al., 2021). (Quoted by Rahman et al., 2022)

A certain **risk exposure (Es)** and **economic value (W)** of the element can be associated with the element at risk. The risk exposure is defined as the probability that a certain element will be exposed at the time when a potentially hazardous phenomenon occurs. Fundamentally, it pertains to the extent and manner in which a particular phenomenon interacts with the vulnerable elements, that means that it depends both on the intensity of the event and on the element characteristics (Brogini, 2010).

$$Es = p(E = x, y, z, t)$$

Specific risk (Rs) is described as the expected degree of damage related to a particular potentially harmful event.

$$Rs = H\, x\, V\, x\, Es$$

In **total risk (Rt)**, on the other hand, the value of the element at risk is also taken into account (as shown in the formula). So, "total risk is the expected number of casualties and damages, due to a particular phenomenon. It represents the total damages resulting from the event" (Barbero, 2011).

$$Rs = H\, x\, V\, x\, Es\, x\, W$$

Ultimately, it is possible to identify a **residual risk (Rr)** which is the level of risk that remains despite the mitigation and prevention measures put in place. These mitigation measures generate a change in the level of risk equal to ΔR. This is an important concept as it demonstrates the effectiveness of a proposed solution to mitigate a risk. The difficulty clearly lies in translating all mitigation operations mathematically, using statistical approaches.

$$Rr = Rt - \Delta R$$

2.4.2 Landslide hazard assessment

"*Landslides, as one of the major natural hazards, account each year for enormous property damage in terms of both direct and indirect costs in mountainous regions. In recent years, risk analysis and assessment has become an important tool in addressing uncertainty inherent in landslide hazards*" (Dai et al., 2002).

Assessing the hazard of a landslide basically means carrying out a prediction of what **kind** of landslide may develop, with what **intensity**, as well as **where** and **when** the landslide may occur. So, hazard assessment analyses in which way controlling factors influence dangerous phenomena, enabling mitigation measures to reduce risks and minimize damage.

2.4.3 Methods

Several methods can be used for the hazard assessment, which are:

- heuristic methods
- statistical methods
- deterministic method

Heuristic methods are based primarily on knowledge, in other words, they are subjective, qualitative estimates influenced by the experience of those who formulate them.

"The goal of **statistical methods** is to establish statistical correlations between information about past landslides and a set of factors that are presumed to have a direct or indirect influence on the occurrence of landslides" (Cascini, 2014).

Clearly, what is important for the success of this method is the availability of a historian with events that occurred in the past.

The initial premise is that the factors that caused slope movement in the past are the same factors that will impact future landslides. This model can be considered an objective model in that it is based on statistical data, and its reliability is related to the quality and quantity of data available for the case study. However, some subjectivity remains present, associated with the selection of parameters to be used in the model and the mode of data collection (Brogini, 2010).

To enhance our comprehension of how past rockfalls serve as effective proxies for delineating future hazards, it is valuable to compare the geological and geomorphic characteristics of individual rockfall events with the cumulative amalgamation of numerous events (Borella et al., 2019).

The **deterministic methods** rely on the utilization of mechanics-related theories, such as the theory of limit equilibrium, for instance. These models allow a stability value, called the factor of safety, to be calculated quantitatively.

A purely deterministic hazard assessment can be carried out exclusively for individual slopes or limited-size areas, as long as there is sufficiently detailed geotechnical knowledge of the subsurface (Bolt et al., 2009).

In fact, in order to obtain the resolution of the physical laws used in these models, knowledge of point geotechnical data is required, so in situ surveys and laboratory tests are essential (Brogini, 2010).

It is necessary to specify that what has a major impact on the **choice** of methodological approach to be adopted is the selection of the **working scale**. Even though theoretically any method could be adapted to any working scale, it is important to consider that there may be not insignificant limitations.

Indeed, the use of a statistical method could be problematic on a detailed scale or in areas of limited size, as the number of samples representative of the phenomenon may not be sufficient. On the other hand, a deterministic approach, such as calculating the factor of safety, might have disadvantages when applied on a regional scale (Aleotti and Polloni, 2005).

In addition, an ideal hazard mapping model should be able to identify areas with a specific probability of events occurring in a given time period and with a certain magnitude. “In other words, an approach that integrates **spatial**, **temporal** and **magnitude** probabilities into a single model, taking into account the complexity of various triggers. However, these models are still being researched and may take some time before they are fully implemented in practice” (Abella and Van Westen, 2001).

3. Hazard in Chianocco Gorge: unstable blocks

3.1 Introduction

This chapter proves to be the most substantial, providing a detailed analysis of the case under consideration of Chianocco Gorge, marked by the presence of potentially unstable blocks. Meticulous attention is devoted to examining various methodologies for **estimating the volume** of these unstable blocks.

Moreover, emphasis is placed on the necessity for **access** to the study area, primarily concerning the needs of tourists, who represent the primary element at risk.

In addition, this section investigates the crucial concept of **land use** and **land cover**, exploring their close connection to susceptibility, especially within the context of tourism activities.

Lastly, a critical aspect of risk assessment, namely **vulnerability**, is explored, analysing the diverse steps that contribute to the formation of vulnerability curves.

3.2 Photographic documentation of unstable blocks

Going into the details of the case study of this thesis, along the walls of Chianocco Gorge, several unstable and unsafe blocks were identified.

Being an area of tourist interest, risk identification was of paramount importance and was followed by the unavoidable temporary closure of the zone, to allow the implementation of the necessary safety and monitoring measures, which will be analysed later.

Thanks to the consultation of the executive project carried out by Eng. Casale, it was possible to trace, first of all, the **photographic documentation** of the unstable rock blocks. It is undeniable to claim that the availability of these images is of enormous help in understanding the case, as it gives a concrete idea about what the size of the potentially unstable blocks are.

Furthermore, it was feasible, as will be see in the next paragraphs, to estimate the volume of the main unstable block, referred to as the “Pillar”, by dividing it into smaller sections.

Potentially unstable situations were identified both along the wall located at the hydrographic right and at the mouth of Chianocco Gorge.

Specifically, on the wall to the hydrographic right are blocks marked **L**, **M**, **U** and **V**. An overall view of these blocks is in *figure 24* and, in *figure 25*, with a closer view.

Figure 24 - Overall recovery of the wall in the hydrographic right (blocks L, M, U, V).

Figure 25 - Detail of the wall in the hydrographic right (blocks L, M, U, V).

In the following photographic shots, individual unstable blocks along this wall are shown in greater detail (*figures 26, 27, 28, 29*).

Figure 26 - Detail of block L.

Figure 27 - Detail of block M.

Figure 28 - Detail of block U.

Figure 29 - Detail of block V.

Also, on the same wall, downstream of the gorge, detachment niches can still be recognized, which are related to some previously monitored blocks, named with the letters **N**, **O**, **P** and **Q** (*figure 30*). These detachment niches indicate how the area is prone to rockfall and how preventive action is therefore fundamental to avoid damage. It is no coincidence that, when evaluating the risk of a landslide, conducting a thorough study of previous perilous occurrences at the same site is very important.

Figure 30 - Wall in the hydrographic right where the detachment niches of some previously monitored blocks are visible (N, O, P, Q).

At the mouth of the Gorge, another area exhibits signs of instability and potential detachment (*figure 31*), and therefore is a section to be secured.

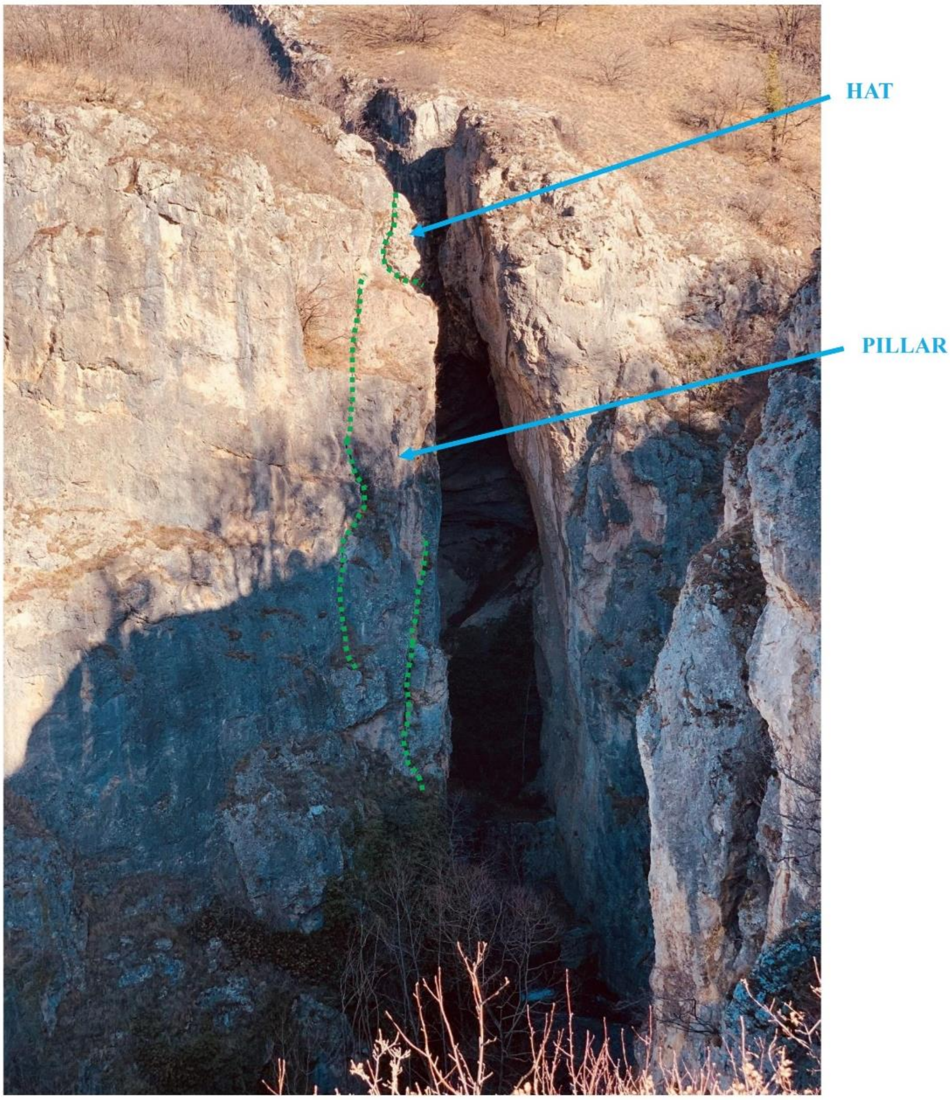

Figure 31 - Gorge mouth: overall view of the sector related to the "Pillar" and "Hat".

In particular, there are two main blocks that are in a critical situation in this section: one is more elongated in shape and is referred to as a "**Pillar**" (*figures 32, 33, 35*) and the other at the top referred to as a "**Hat**" (*figure 34*).

As can be seen from *figure 30*, given the size of the "Pillar", it is intuitive how this is the most dangerous rock block and therefore requires the most effort in securing it.

More pictures showing these two blocks from different viewpoints follow, thus enabling a better understanding of the dimensions of the problem.

Figure 32 - More detailed view of the top of the "Pillar" and "Hat".

Figure 33 - Similar shot to the previous one, but with different angle.

Figure 34 - Close-up of the "Hat".

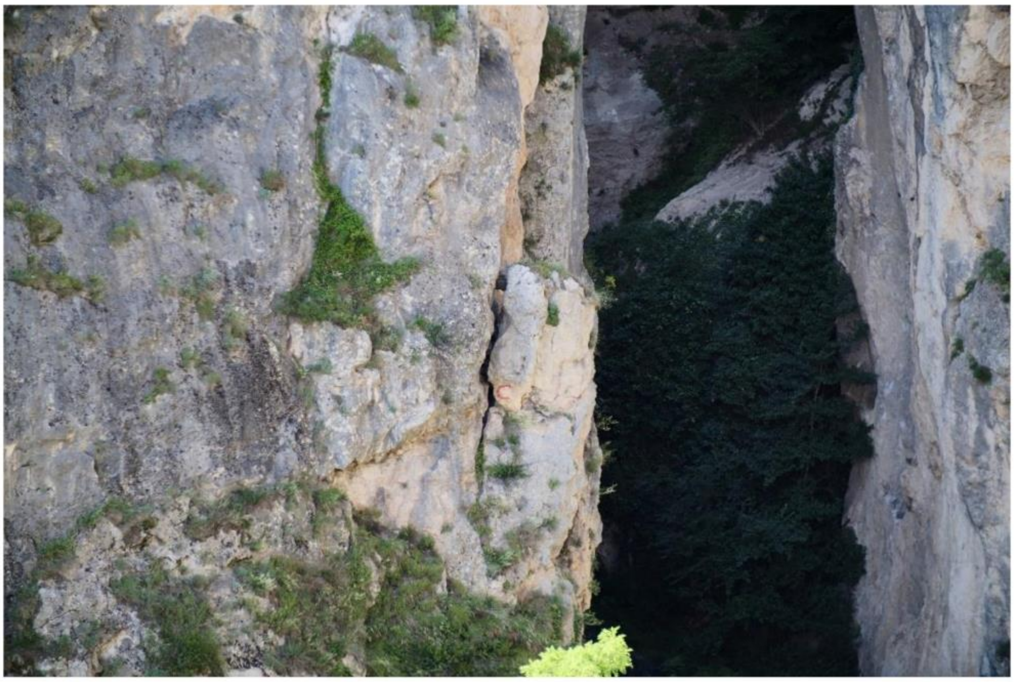

Figure 35 - Lower part of the "Pillar".

In the lower part of the “Pillar” sector, there is in detail a photo of the historically monitored element at the point defined as “**C**” (*figure 36*).

Figure 36 - Detail of the lower part of the “Pillar”, at the historically controlled element at point “C”.

Figure 37 - Drone shot of the northern flank of the “Pillar”.

Figure 38 – "Pillar" shot frontally by drone.

Figure 39 - View of the top of the blocks defined as "Pillar" and "Hat".

Figure 40 - Top of the northern flank of the "Pillar", taken by drone.

Going down to the details of the "pillar" and "cap" sector, blocks marked **H**, **2** (*figures 41, 42, 43*) and **E** (*figure 44*) were identified.

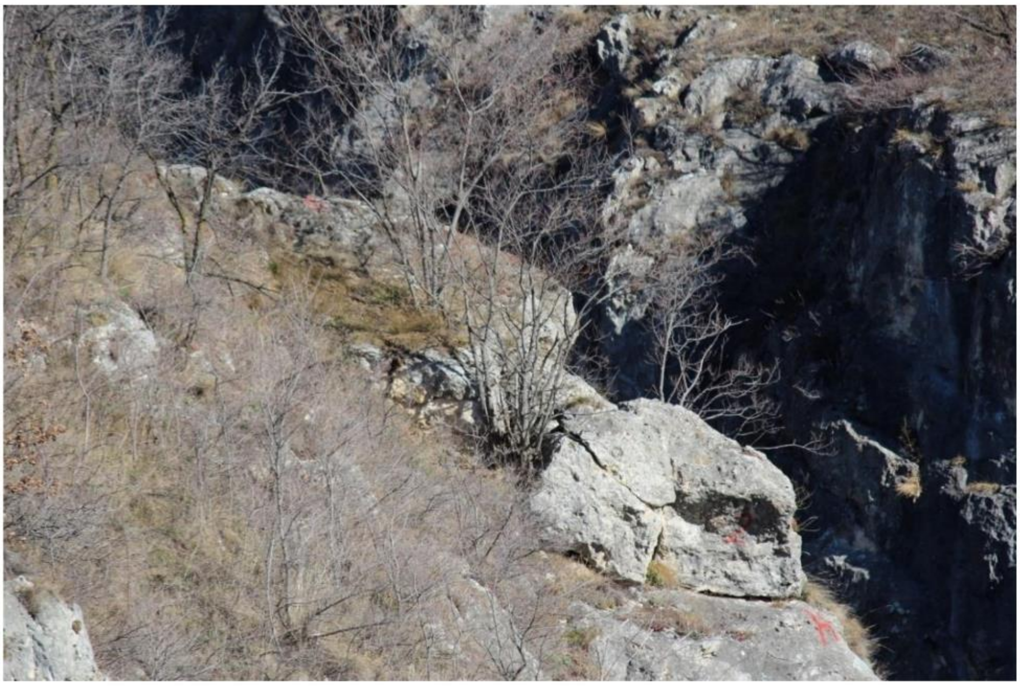

Figure 41 - Detail of blocks H and 2.

Figure 42 – "Hat" detail and blocks H and 2.

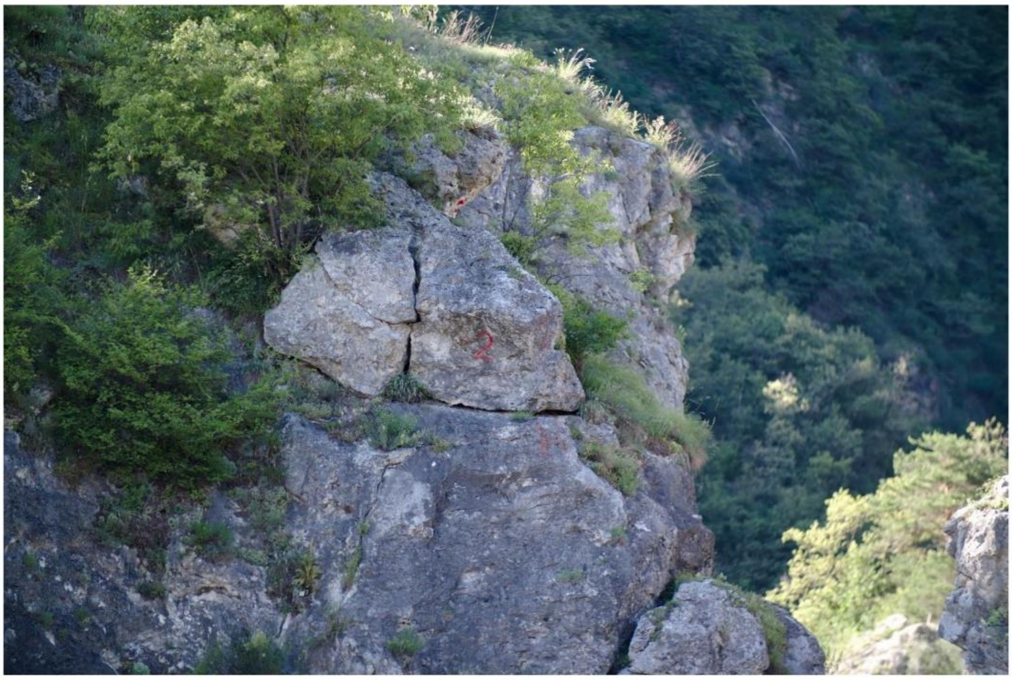

Figure 43 - Blocks H and 2: frontal shot.

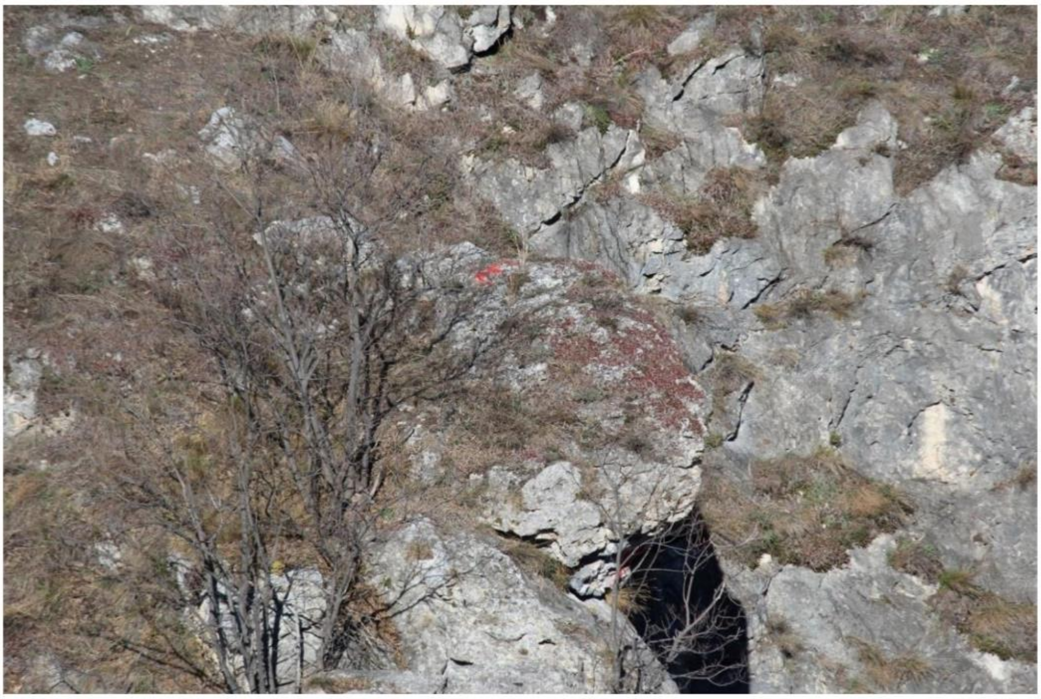

Figure 44 - Block E.

3.3 Blocks volume estimation in Chianocco Gorge

Calculating the volume of a rock block is of paramount importance in situations such as the Chianocco Gorge case study. In fact, the rock blocks volume turns out to be an important **input value** for the later steps of risk assessment. For example, an error in estimating the volume of the rock block could potentially result in under sizing protective measures.

Therefore, it is crucial to delve into the various existing **surveying methods** for determining the rock volume. This allows for the selection of the most suitable method on a case-by-case basis, ensuring accurate and effective protective work.

There are several advanced and accurate surveying methods for determining the volume of a rock formation, each with its own applications and advantages. Some of the most widely used methods include *drone photogrammetry*, *traditional topographic surveying*, *terrestrial laser scanning*, and the use of advanced technologies such as *LIDAR*.

- **Drone photogrammetry** (figure 45a) emerged as an effective method for obtaining detailed 3D models of rocky areas. By capturing aerial images, a drone can generate a three-dimensional model that allows accurate volume calculations using gridded sections. This approach combines the power of drone technology with photogrammetry software to produce accurate and detailed results.
- **Traditional topographic surveying**, based on terrestrial instruments such as total stations (figure 45b) and levels, remains a reliable methodology for measuring the volume of rock formations. However, it may require more time and effort than automated methods, but it is often employed in situations where accuracy is crucial, and topography is complex.
- **Terrestrial laser scanning** is an advanced approach that uses a laser beam to survey the surface of rock with high accuracy. This technique provides detailed point-by-point data, enabling the creation of highly accurate three-dimensional models and facilitating volume calculation through advanced analysis.
- **LiDAR** (Light Detection And Ranging) sensor (figure 45c) installed on a ground-based, airborne, or space-based platform. The use of lasers from aircraft or satellites allows for extensive coverage and high point density, making this technology ideal for large rocky areas. LiDAR sensors capture the x, y, and z

coordinates of both artificial and natural features by emitting light pulses toward the ground and recording the reflected radiation. The result is a three-dimensional point cloud representing the specified area.

Figure 45 - a) Drone photogrammetry; b) total station; c) LiDAR (courtesy of Maschio P. and Cina A.).

Figure 46 illustrates the Ponte Val Formazza example, showcasing the outcomes derived from the three remote sensing techniques presented in *figure 45*.

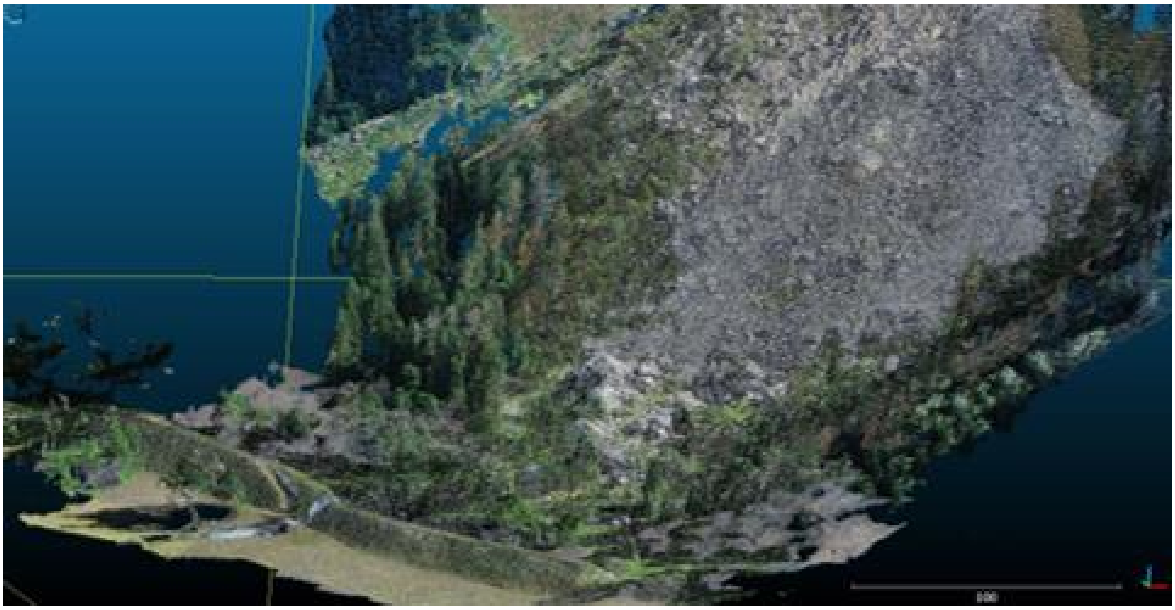

Figure 46 – Example of result of survey over a large area with different remote sensing techniques, in Ponte Val Formazza (courtesy by Cina A.).

Figure 47 provides an overview of the **non-contact survey procedure**. The outcome of these techniques is the Digital Surface Model (DSM), depicting the topography of the

Earth's surface, encompassing various objects such as trees, buildings, and other features.

Digital Surface Models (DSMs), generated through LiDAR or photogrammetry, surpass traditional topographic mapping by offering high-resolution data, capturing intricate details often missed by conventional maps based on field surveys. The precision in elevation measurements facilitates accurate calculations of slope, aspect, and other terrain characteristics.

Moreover, this digital elevation model serves various purposes beyond rock volume estimation. It can be integrated into software applications like RocFall for conducting 2D rockfall simulations.

As proved by Kakavas et al. (2023), the spatial resolution of the Digital Surface Model (DSM) varies depending on the employed technique. In the context of rockfall simulation with RocFall software, UAV emerges as the most suitable technique, yielding the most accurate and realistic results.

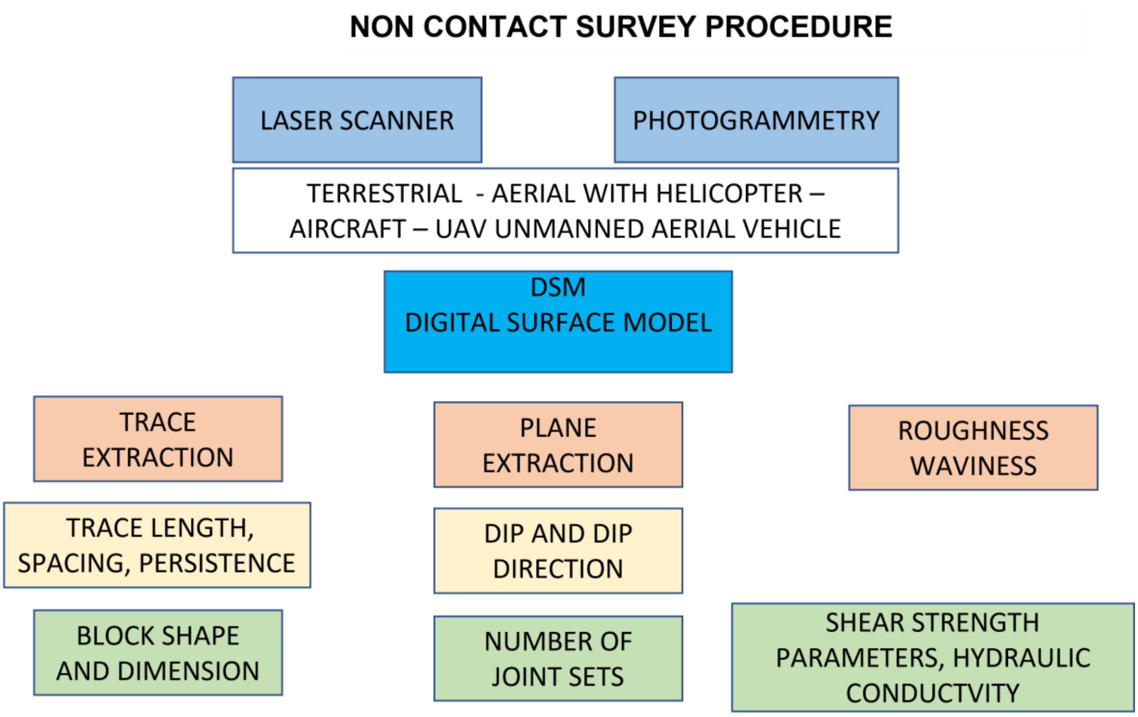

Figure 47 - Overview on non-contact survey procedure.

Each method has its advantages and limitations, and the **choice** depends on the specific needs of the project and on the economic availability. The combination of modern technologies and traditional approaches provides a diverse range of tools to address the challenges of calculating rock block volume accurately and efficiently.

For example, through **UAV** (*Unmanned Aerial Vehicle*, like drone and LiDAR) surveys, larger areas can be covered, and data can be obtained at **larger scales**, reducing the need for extensive fieldwork. Most importantly, this approach enhances **safety conditions** for fieldwork in rockfall areas (Zabota et al., 2023).
In addition, several recent studies examined how the **temporal resolution** of data collection and various decisions in data processing can impact the estimated volumes of rockfall (Walton and Weidner, 2023).

An interesting study carried out by Zabota et al. (2023) demonstrates the potential of photogrammetry and LiDAR as effective alternative to the traditional approach of assessing rock dimensions in the field using a measuring tape. Specifically, it shows that "*there are no statistically significant differences between the measurement method with respect to rock* ***dimensions*** *and* ***volumes*** *and when modelling propagation probability and maximum passing heights*", and then goes on stating that "*on the other hand, large differences are present with* ***maximum kinetic energies*** *where LiDAR point cloud measurements achieved statistically significant results different from the other two measurements".*

From the study's findings, so, it was possible to deduce that all three rock measurement methods are suitable for delineating the extent of rockfall propagation areas. However, when it comes to planning technical protection measures, a more detailed approach is necessary. Specifically, careful consideration should be given to selecting the measurement method, with a focus on ensuring that actual kinetic energies are not overlooked. Inadequate planning of protective measures may result in insufficient risk reduction efforts for mitigating rockfall hazards.

What described so far, however, is only the image acquisition phase. Once the images are acquired by, for example, photogrammetry or LiDAR, graphics software is used to **process the images** and generate a 3-D model. The graphics software attempt to reconstruct the three-dimensional geometry based on the information obtained from the images. Finally, through the **summarized sections method**, the volume of the rock block in question is finally estimated.

In the specific case of this thesis, the volume estimation was done on the largest block as well as on the “Pillar” at the mouth of **Chianocco Gorge**. A drone was used for image acquisition of this rock block.

After acquiring a base of photos taken by **drone**, it was possible to estimate the volume with five discrete sections of the “Pillar” (*figure 48*). The illustration below depicts these sections of the “Pillar” and was crafted by the engineer Casale, that overseeing the case study of Chianocco Gorge. This figure also shows the elevation measurements, which are needed in the next step for the calculation of the block volume, by means of the summarized sections approach.

The **summarized sections method** (*figure 49*) involves dividing the three-dimensional shape of the rock into regular horizontal sections and then calculating the total volume by summing the volumes of each section. Specifically, we subdivide the three-dimensional model obtained in the previous steps into regular horizontal sections, generally parallel to the ground. Next, the volume of each horizontal section is calculated using its geometric data and dimensions. Finally, the sum of all the partial volumes obtained from the individual sections is made to obtain the total volume of the unstable rock.

This method is particularly useful in situations where the shape of the rock is complex and cannot be accurately represented by simpler methods.

However, it is important to note that the accuracy of the result depends on the precision of the source data and the correct application of the method when dividing into sections and calculating volumes.

Finally, considering a specific gravity of the rock equal to 25 Kn/m^3, a total mass of 11159,25 kN was obtained.

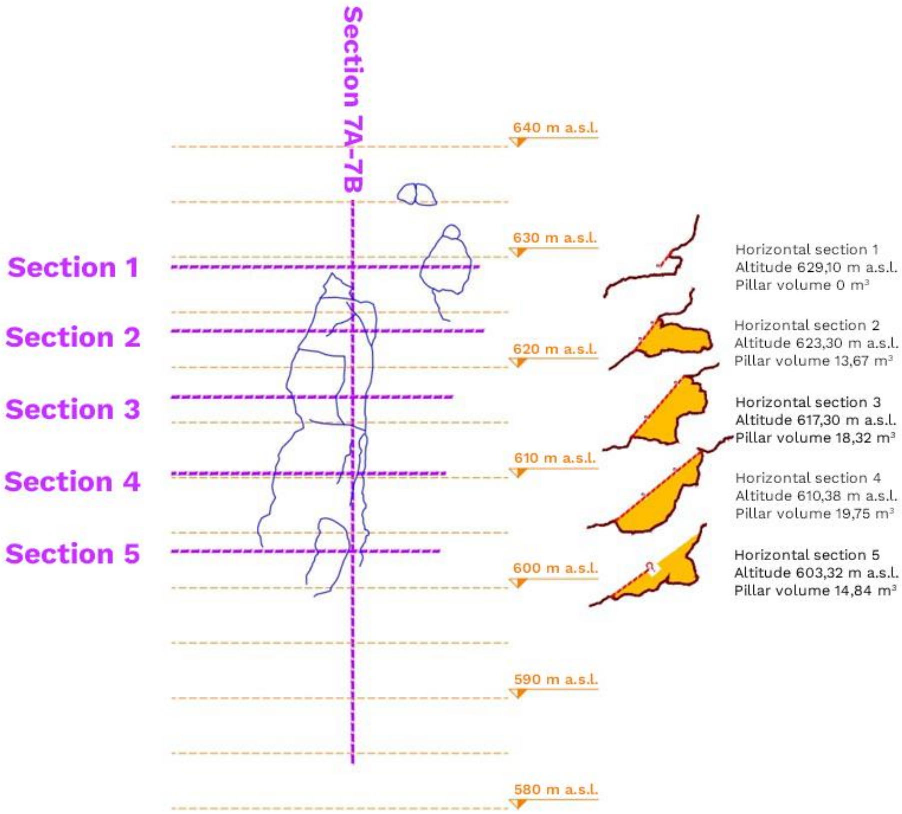

Figure 48 - Schematic representation of the discrete sections to estimate the volume (Casale).

	Area (m^2)	Distance (m)	Volume (m^3)
Head	0		
		-	-
Section 1	0		
		5,12	34,99
Section 2	13,67		
		6,00	95,97
Section 3	18,32		
		6,92	131,72
Section 4	19,75		
		7,06	122,10
Section 5	14,84		
		4,15	61,59
Base	14,84		
		Total result	446,37

Figure 49 - Summarized sections method applied to the "Pillar" block (Casale).

3.4 In-Situ Block Size Distribution in jointed rock mass

The **interaction of discontinuities** within a jointed rock mass results in in-situ blocks with varying three-dimensional (3D) geometries.

Of course, these discontinuities go over time to change the geomechnical characteristics of the intact rock, that is, they constitute the weak point of the rock mass. Basically, it is possible to state that the dimensions and the shape of these rock blocks within a rock mass assembly exert significant control over the engineering characteristics of the rock mass. They dictate crucial factors such as the failure pattern of a rock face and the optimal support and surface restraint approach.

This is concept expressed by the Rock Mass Index (RMi), that was conceived as a valuable tool, offering insights into the **diminished strength of intact rock** resulting from the presence of discontinuities (Palmström, 1996).

For example, the distribution of block sizes can have a substantial impact on the permeability and stability of a rock mass, serving as a key consideration in reinforcement design. In particular, the shape of rock blocks influences engineering properties like excavation ease, wave propagation, excavation and slope stability (Kalenchuk et al., 2006).

These are the reasons why is considered an important topic and different approaches for evaluating the volume distribution of blocks can be identified in the scientific literature. Furthermore, addressing this challenge is closely tied to the necessity of applying the different indices for rock mass classification (RMi, GSI…), which require precise determination of block sizes, as described by Kim et al. in 2006.

It is essential to specify that it is convenient to talk about **statistical distribution** of block volume, rather than to identify a single deterministic mean value. In fact, as joint spacings typically exhibit considerable variation, the contrast in dimensions between smaller and larger blocks can be noteworthy.

As specified by Poropat and Elmouttie (2012), the variation in sizes of these blocks is denominated in literature *in-situ block size distribution* (IBSD).

This preference arises from the diverse **uncertainties** inherent in the problem. In fact, the estimation of rock block volume is intricately linked to factors such as the number, the orientation, the spacing, and the joints persistence.

Joint spacing refers to the separation distance between individual joints within a given joint set (Palmström, 2000). As defined by Brady and Brown (1992) and reported by Kim et al. (2006), *persistence* refers to the areal extent or size of a discontinuity within a plane.

In particular, both **orientation** and **spacing** are measurable, and their variability can be estimated. On the other side, assessing **persistence** proves to be especially challenging and intricate. Indeed, to ensure safety, the blocks are often treated as entirely unconnected.

Nevertheless, by assuming joints as persistent, as is common in most designs, there is the tendency to underestimate the sizes of rock blocks. Furthermore, a lack of comprehension regarding the strength of rock bridges may result in underestimated rock mass strengths, leading to unnecessary expenses on rock support (Kim et al., 2006).

So, starting from the necessity to statistically examine how the distribution of **rock bridges**, considering joint orientation, spacing, and persistence combinations, impacts the actual size of each individual block, different studies were conducted and compared with each other.

Depending on site's specific conditions and accessibility, surveying methods to establish the IBSD can be **indirect**, generally less accurate, or **direct**, which offer greater precision. Moreover, these methods undergo continuous evolution, keeping pace with advancements in technology.

A noteworthy paper authored by Palmström (2000) outlines several main traditional methodologies:

- **Directly in-situ or in drill cores**, by measuring the average dimensions of several representative blocks. It is advantageous for smaller blocks, where assessing all discontinuities would be more intricate.
- **From joint spacings**, through the relationship obtained by assuming 90-degree angles between the joint sets ($V_b = S_1 \, x \, S_2 \, x \, S_3$), with the option to consider the average joint spacing S_a in the event of multiple sets.
- **From joint frequency measurements** (Jf=1/S), similar to joint spacing measurements.

- **From the volumetric joint count** (**Jv**), a metric quantifying the number of joints within a unit volume of rock mass (Palmström, 1982, 1985, 1986). This value can be readily computed from standard joint observations, relying on measurements of joint spacings or frequencies: $J_V = 1/S_1 + 1/S_2 + 1/S_3$. Then, through a correlation is possible to reach the volume value: $V_{b_0} = \beta \times J_V^{-3}$, where β is the block shape factor.
- **From weighted jointing density measurements** (**wJd**), that relies on measuring the angle between each joint and the surface or borehole, with the aim to extract more precise information.

A method proposed by Smith (2003) for measuring block sizes and shapes involves compiling dihedral angles against the spacing of consecutive discontinuities in linear samples. In drill cores, whether oriented or not, this approach is applied by measuring the length and dihedral angles between the terminal faces of intact core pieces.

The **traditional techniques** bring to the estimation of one or a few volumes within the wall, relying on simplifying assumptions that often diverge significantly from reality. Indeed, these methods fall short in capturing the substantial **heterogeneity** inherent in naturally occurring rock clusters.

Contrastingly, addressing heterogeneity was a focal point in recent research advancements. These developments not only leverage cutting-edge **acquisition technologies** but also excel in generating multiple volume simulations through sophisticated **numerical models**.

For example, Kim et al. (2006) created different combinations of geometric discontinuity conditions using orthogonal arrays with the assistance of distinct element analysis tools (UDEC and 3DEC). Afterwards, through numerical simulation, equivalent block area or volume and their distributions were provided.

In conclusion, correlation analysis was conducted to establish a relationship between the block sizes obtained from the numerical model simulation, and those predicted by an empirical equation proposed by Cai et al. (2004).

Kalenchuk et al. (2006) also chose to employ 3DEC, developed by Itasca, to construct the model for their study. This enabled the generation of synthetic blocks, so of cumulative volume distribution. The Block Shape Characterization Method, as coined, was devised and calibrated using artificial joint data. An evaluation of field data substantiated its application and validity, confirming its effectiveness through comparison with visual inspection results. This methodology finds widespread application and utility in the field of rock engineering.

Poropat and Elmouttie (2012) introduced a method that leverages Monte Carlo simulations to model Discrete Fracture Network (DFN) geometry, incorporating advanced representations of fractures alongside a robust polyhedral modeling algorithm.

Basically, a variety of **statistical distributions**, including log-normal, Fisher's, Weibull, and Gamma distributions, can be utilized for statistical interpolation of the data. Clearly, it is crucial to determine, through rigorous evaluation with statistical **tests**, which distribution best fits the experimental data for each set of measurements.

Methods described in the scientific literature revolve around surveys of rock walls designed to identify potentially unstable blocks. Alternatively, examinations of fallen blocks are conducted, where the calculation of block volumes is conducted to establish the Rock Block Size Distribution (RBSD). The geomechnical survey results yield a distribution, enabling the volume to be regarded as a continuous random variable. In this scenario, the assessment will be more dependable than the one relying on the block survey at the base of the slope, even though the range of variability will be broader.

The following is the relationship expressing the **volume of a block**, in the simplest case with three families of discontinuities Ki, Kj and Kk:

$$V = \frac{\|\vec{\mu_i}\|\|\vec{\mu_j}\|\|\vec{\mu_k}\|}{|\sin \gamma_{ij}||\cos \delta_{k-ij}|} = \frac{S_i S_j S_k}{q} \quad (1)$$

where the vectors at the nominator correspond to the director vectors of the three families of discontinuities, and their norm corresponds to their spacing Si, Sj, Sk, and

$$q = \sin \gamma_{ij} \cos \delta_{k-ij} = \sin \gamma_{jk} \cos \delta_{i-jk} = \sin \gamma_{ik} \cos \delta_{j-ik} \quad (2)$$

where, according to the terminology used by Palmstrøm (1996), the angles between pairs of discontinuity families are γ_{ij}, γ_{ik}, γ_{jk} and δ_{k-ij} (δ_{i-jk}, δ_{j-ik}) is the angle between the director vector $\vec{\mu k}$ and the direction normal to the other two director vectors $\vec{\mu i}$ and $\vec{\mu j}$.

In the probabilistic assessment of ISBD, it is prudent to consider the variability in the joint spacing value. This involves assuming that the **spacing distributions**, that is the frequency density curves (CDF or FSi(si)), for the three families of discontinuities are independent of each other.
Consequently, the **volume frequency density curves** take the following form:

$$ISBD = F_V(v) = \frac{F_{S_1}(s_1)F_{S_2}(s_2)F_{S_3}(s_3)}{q} \quad (3)$$

3.5 Elements at risk and access needs

As previously mentioned in the terminology, the elements at risk include the population, the properties, the economic activities, the assets, and public services, potentially exposed to risk in a given area.

In the specific context of Chianocco Gorge, situated in a mountainous region, the main element at risk is undeniably represented by the **population**, including in particular tourists and sports enthusiasts who frequent the Reserve. Indeed, it is well known how, over the years, this area was a point of attraction for the beauty that nature offers, tourist trails and via ferrata routes.

The charm of the Reserve is certainly given by the unique stand of holm oaks that grow wild in Piedmont, but it is further enriched by the beauty of the **Gorge**, a narrow gorge carved over the centuries by the **Prebèc stream** within the massive rock face that rises behind Chianocco, with vertical walls that reach a height of about 50 meters (Chiaretta, 2022).

The **Via Ferrata** of Chianocco Gorge (temporarily closed) is a path that originates from the municipality of Bussoleno. It traverses the Gorge created by the Prebèc stream and is highly captivating with a scenic perspective (*figures 50, 51*).

In March 2020, the mountain guide responsible for conducting routine inspections of the Chianocco Gorge walls observed unusual movements in the monitored blocks positioned at the entrance of the Gorge. "Given the size of the boulders and their location, by *executive determination of the Cottian Alps Protected Areas Management Authority No. 58 of March 11, 2020*, it was deemed appropriate to provide for the **closure of the Ferrata** as a precautionary measure. The Municipality of Chianocco by *union ordinance No. 3 of March 11, 2020* also closed the access path to the Ferrata" (from Parchi Alpi Cozie).

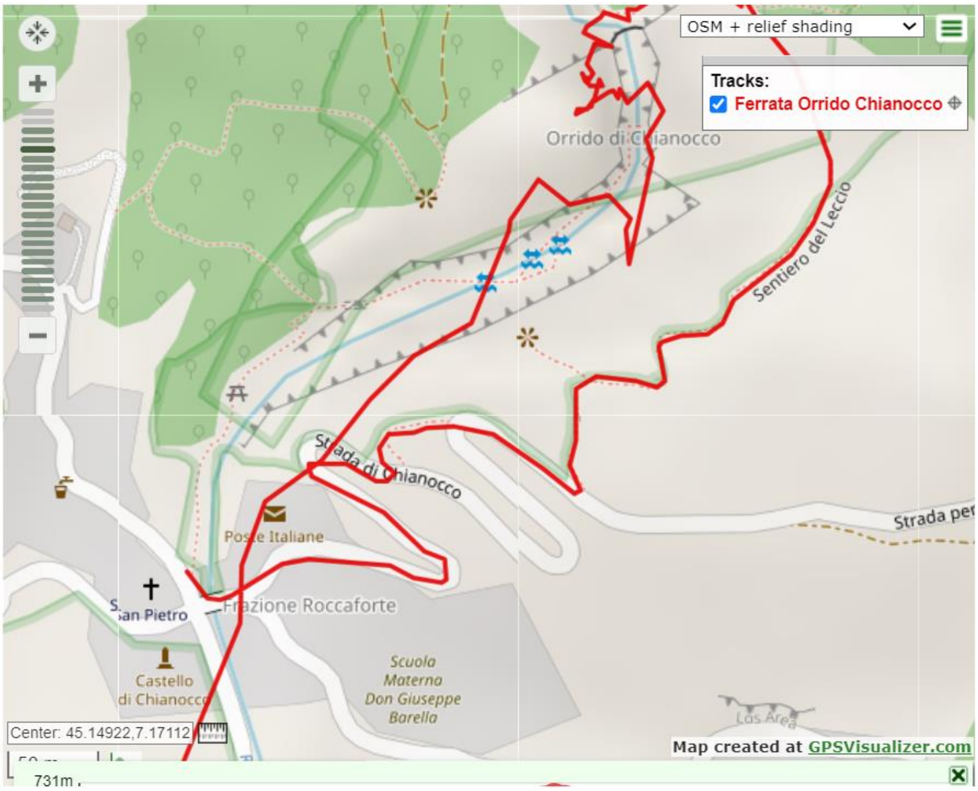

Figure 50 – Route of the Chianocco Via Ferrata (from ferrate365).

Figure 51 - Tourists along the via ferrata near the Gorge (from Gulliver).

The Chianocco Nature Reserve boasts one of Italy's most picturesque **hiking** trails – a loop spanning 6.77 km with a maximum elevation of 955 m (*figure 52*). The route follows the Rio Prebech until it reaches a tunnel that leads inside the gorge (Zanchi, 2020).

Figure 52 - Hiking trail in the Chianocco Reserve (from Wikiloc).

The pathway within the Gorge is presently off-limits as a safety measure (*figure 53)*. However, there is an alternative accessible stretch that permits observation of the narrow gorge from an alluvial shelf situated behind it (*figure 54*).

Numerous vantage points along the way also offer opportunities to view the "Molè Gullies" and witness erosions on steep slopes (Chiaretta, 2022).

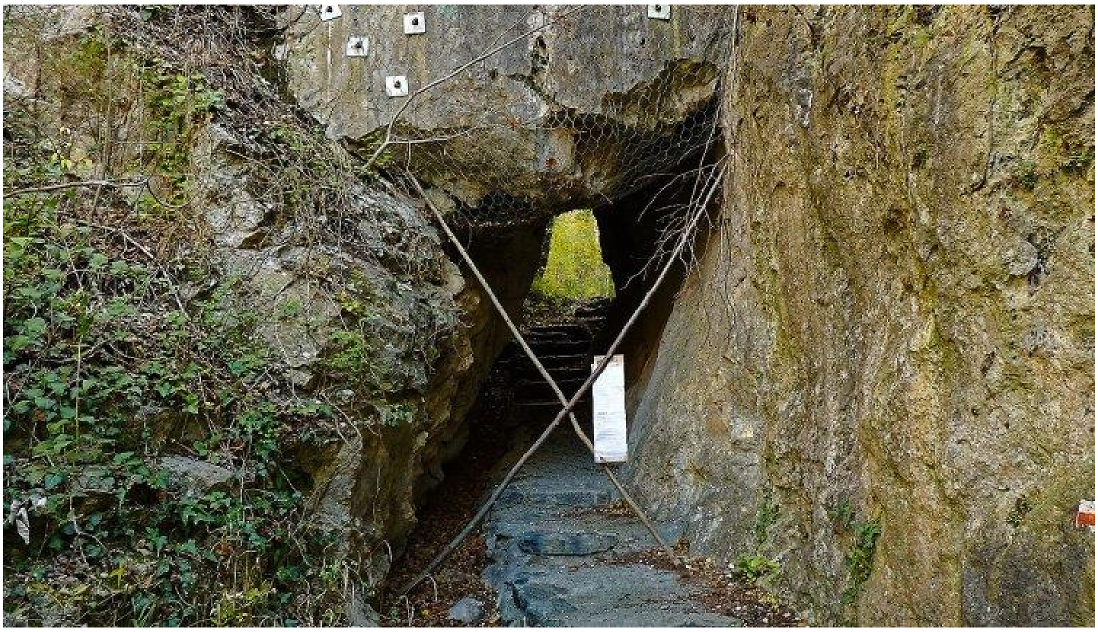

Figure 53 - Tunnel leading to the Gorge, temporarily closed (Chiaretta, 2022).

Figure 54 - View of the Orrido from the floodplain (Chiaretta, 2022).

3.6 Land use and land cover

At this point, it is fitting to open a parenthesis on land use and land cover, which is clearly related to the concept of tourism and with the concept of landslides **susceptibility**.

Limited attention was devoted to exploring the impact of land-use and land-cover (LULC) changes, which are notably frequent at lower altitudes and in close proximity to urbanized areas, on the propagation of rockfall and the associated risks (Farvacque et al., 2019).

The analysis of publications and citations indicates a prevailing trend where a majority of articles lack a substantial focus on the correlation between land-use and land-cover (LULC) and landslides, despite a burgeoning interest in this subject (Quevedo et al., 2023).

In fact, the way in which land is utilized and its overall cover play a pivotal role in shaping the vulnerability to landslides of an area, especially when considered in the context of tourism activities. The intensity and nature of human activities, such as **urbanization** and **tourism** infrastructure development, can significantly influence the stability of the terrain.

So, a closer examination of the intricate links between land use, land cover, tourism, and landslide susceptibility, becomes imperative in devising holistic and sustainable approaches for land management and hazard mitigation.

Going into more detail about the two terms, as for the European Environmental Agency, **land use** is intricately tied to the socio-economic characterization (functional dimension) of areas, distinguishing between residential, industrial, agricultural purposes, and more. Notably, connections to **land cover** exist; indeed, it might be feasible to deduce land use from land cover and vice versa.

However, circumstances are frequently intricate, and the connection is not always straightforward. Unlike land cover, land use is challenging to “observe”. For instance, determining whether grasslands are utilized for agricultural purposes can be difficult. The nuances in defining land use versus land cover have repercussions on the formulation of classification systems, data collection, and information systems in general (European Environment Agency, 2004).

So, **land cover** pertains to the physical extent of the earth's surface. The primary classes of land cover LUCAS (Land Use/Cover Statistical Area Frame Survey) nomenclature include:

A00	Artificial land
B00	Cropland
C00	Woodland
D00	Shrubland
E00	Grassland
F00	Bareland
G00	Water
H00	Wetland

Figure 55 - Land cover classification (from Eurostat regional yearbook 2011).

Land use encompasses the socioeconomic function of the land. The principal classes in the LUCAS land use nomenclature are as follows:

U110	Agriculture
U120	Forestry
U130	Fishing
U140	Mining and quarrying
U150	Hunting
U210	Energy production
U220	Industry and manufacturing
U310	Transport, communication networks, storage and protective works
U320	Water and waste treatment
U330	Construction
U340	Commerce, finance and business
U350	Community services
U360	Recreational, leisure and sport
U370	Residential
U400	Unused

Figure 56 - Land use classification (from Eurostat regional yearbook 2011).

Anyway, what deserves emphasis is that frequently, there is a tendency to enhance public services at the **detriment of nature**, as seen in practices like deforestation. This trend was particularly prevalent in the past when environmental concerns weren't as prioritized. However, even today, instances persist where economic interests take precedence over environmental considerations.

With respect to **deforestation**, the presence of forest cover plays a vital role in shielding mountainous slopes from weathering and mass wasting processes. The intricate network of roots within the soil anchors it, maintaining **slope stability**.

However, the rise in population escalated the need for both wood and land for agriculture, resulting in the disruption of slopes in nearly all mountainous regions worldwide. This disturbance has, in turn, triggered slope instability (Rahman, 2022).

In conclusion, it is possible to state that land use practices and land cover can have a **direct impact** on the occurrence of landslides. **Changes in land use**, such as deforestation, urbanization, or improper agricultural practices, can alter the stability of slopes and contribute to **landslide events**. When natural vegetation is removed or the land is extensively modified, it can lead to reduced slope stability and increased susceptibility to landslides.

Effective land use planning, soil conservation measures, and sustainable development practices are crucial for minimizing the risk of landslides associated with human activities. Future scenarios of landslide susceptibility can offer valuable insights for effective landslide risk management and strategic land use planning (Quevedo et al., 2023).

3.7 Vulnerability

"*Vulnerability is the essential element of risk assessment which refers to the potential degree of loss to the element at risk*" (Ram and Gupta, 2022; quoted by Rahaman, 2022).

Quantifying vulnerability, whether through empirical or heuristic methods, necessitates data obtained from historical rockfalls, which may not consistently be accessible (Mavrouli and Corominas, 2010).

The social, economic, and environmental quantification of vulnerability remains a formidable task in landslide studies, as noted by Fu et al. (2020).

Consequently, the assessment of physical vulnerability is usually conducted by considering the exposure level of elements at risk and the likelihood of loss resulting from landslides (Rahman et al., 2022).

So, the vulnerability to landslide risks is calculated based on the exposure of elements at risk of landslide/susceptibility.

Primarily, to conduct a vulnerability assessment, it is essential to **identify elements at risk**, such as agricultural land, settlements, rangeland, forests, schools, roads, and bridges.

Subsequently, utilizing the landslide **susceptibility map**, exposure maps can be generated to gauge the degree of exposure for these identified elements at risk.

Finally, these **exposure maps** are used to prepare the **vulnerability map** of the area using a geo-statistical approach base: $V = P(D)$, where P is the probability of loss due to landslides and D is the element at risk (Rahaman et al., 2022).

The value assigned to each element at risk is subsequently employed in the calculation of the probability of loss, represented on a scale from 0 to 1. In this scale, zero signifies no loss, while a score of 1 indicates total loss.

So, based on the elements at risk, a landslide vulnerability map can be prepared. Subsequently, merging the maps illustrating hazard and vulnerability enables the creation of a comprehensive **risk map** for the study area (Rahman et al., 2022).

In other words, in **Quantitative Risk Assessment** (QRA), the estimation of rockfall risk for exposed elements involves incorporating each term of the risk components – hazard, exposure, and vulnerability – in the form of probabilities (Farvacque et al., 2019).

In particular, **hazard** encompasses the annual probability of occurrence, commonly evaluated through rockfall inventories (Dussauge-Peisser et al., 2002; quoted by Farvacque et al., 2019).

Exposure refers to the likelihood that a specific element at risk is situated at the impact location during the time of impact, taking into account both temporal and spatial probabilities.

Subsequently, **vulnerability** curves, obtained through the retrospective analysis of documented events, are employed to assess the extent of loss on the elements at risk (Farvacque et al., 2019).

4. Risk management and mitigation

4.1 Introduction

Upon determining the risk level in the assessment process, landslide risk **management** evaluates its **acceptability** and enacts appropriate control measures to **mitigate** the risk if deemed unacceptable.

Therefore, to effectively address the hazard of landslides, it is imperative to adopt innovative methodologies that enhance our comprehension of landslide risks. This, in turn, enables informed decision-making regarding the allocation of funds for the management and mitigation of landslide risks (Dai et al., 2002).

In fact, social and economic losses due to landslides can be reduced by means of effective **planning** and management. These strategies encompass: (a) limiting development in areas prone to landslides, (b) implementing codes for excavation, grading, landscaping, and construction, (c) employing physical measures such as drainage, slope-geometry modification, and structures to prevent or manage landslides, and (d) establishing warning systems (Slosson and Krohn, 1982, Schuster and Leighton, 1988, Schuster, 1996; quoted by Dai et al., 2002).

This chapter initiates by providing a comprehensive analysis of risk **management** using the "ALARP principle" as a guiding method. This section revolves around the concept of risk acceptability, which emerges as one of the most intricate aspects of Quantitative Risk Assessment. The **ALARP principle** enables a visual understanding, depicted through a graph, providing insights into the reasonable extent to which risk reduction can be achieved. By plotting two curves on the same graph—the risk level curve and the mitigation costs curve—it illustrates the intersection point, which denotes the ALARP threshold.

Subsequently, attention shifts to risk **mitigation**, initially outlining the diverse forms of active or passive interventions and the challenges inherent in their selection.

Following this overview, a detailed exploration ensues, delving into the specific risk mitigation **measures proposed** for the case under consideration in this thesis.

4.2 Risk management: ALARP principle

Before delving into a detailed examination of various risk mitigation interventions, it is prudent to briefly address the matter of risk management. Indeed, determining the **threshold** at which the calculated risk becomes **acceptable** or not is a nuanced and intricate process.

From a risk management standpoint, risk criteria serve as the mechanism through which the outcomes of a risk analysis can be translated into recommendations on whether the risk should be tolerated or if there is justification for implementing (additional) measures to **mitigate** it.

The exploration of an accepted risk level for landslide hazards is a recent development, and as of now, there is no established standard in place. Nevertheless, the difficulty lies in ascertaining what level of risk threatened individuals and society are willing to accept, given that each person perceives and acknowledges risks in a unique manner (Song et al., 2007).

Indeed, identifying the limit of risk acceptability turns out to be one of the most complex parts of the Quantitative Risk Assessment (QRA).

To address this challenge, it is advisable to employ the **F–N curve**, tailored to the specific region of interest. This curve delineates the number of fatalities (N) against the cumulative frequency (F) of N on a log–log scale, as advocated by Dai et al. (2002), Song et al. (2007), and Hungr et al. (2016).

Nevertheless, studies reviewing acceptable risk and tolerable risk in landslides, along with examinations of F–N curves, are limited, despite the considerable body of work reported by researchers worldwide (Sim et al., 2022).

Figure 57 shows the F-N curves of different countries.

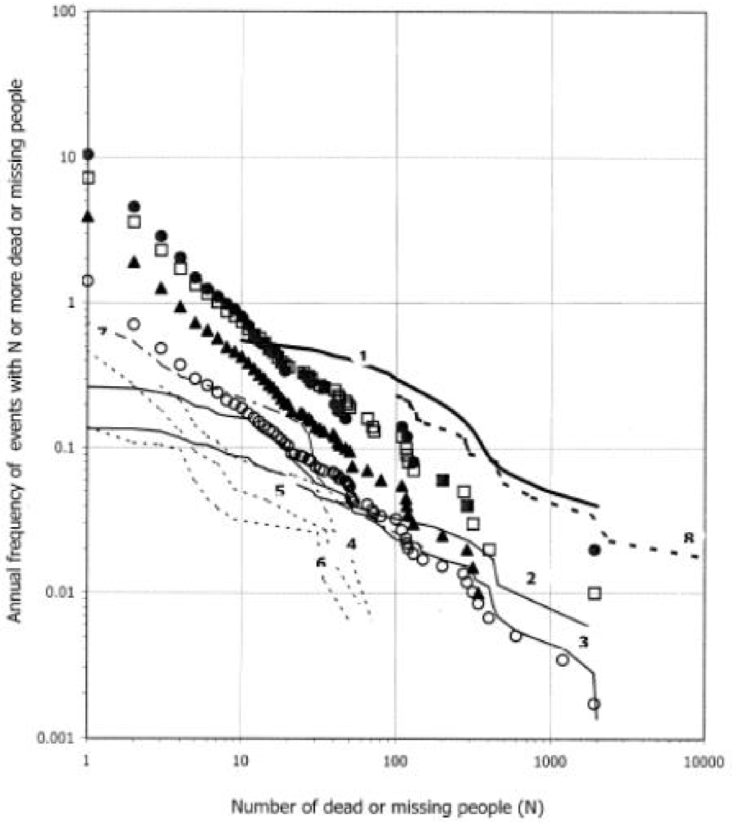

Figure 57 - Comparative analysis of frequency versus consequences (F–N plot) curves on a global scale is illustrated based on data from various regions: 1: Japan (1948– 1996); 2: the Alps (1800–1974); 3: the Alps (1248–1974); 4: Canada (1860–1996); 5: British Columbia (1860–1996); 6: Quebec (1840–1996); 7: Hong Kong (1948–1996); 8: China (1900–1987). (Song et al., 2007)

Moreover, Sim et al., in their article published in "Geoenvironmental Disasters" (2022), delineate the distinction between acceptable and tolerable risk.

In particular, **acceptable risk** denotes a level of risk that the public is willing to accept without considering its management for life and work purposes. Additional expenditure to mitigate such risks is generally not taken into consideration by the public.

On the other hand, **tolerable risk** is a risk that the general public is willing to coexist with to safeguard specific net benefits, trusting that the risk is adequately controlled. The risk level undergoes periodic reviews and is further reduced whenever possible.

A noteworthy concept in this context is the **ALARP** principle (As Low As Reasonably Practicable). In landslide risk management, it refers to a **risk reduction** approach that aims to minimize the level of risk associated with landslides to a point that is both achievable and reasonable. The principle recognizes that it may be impractical or economically unreasonable to reduce the risk to zero, but efforts should be made to bring the risk to a level that is as low as is **reasonably achievable**.

The **graph** below (*figure 58*) illustrates the foundational concept of the ALARP principle. On the x-axis, the graph depicts the mitigation effort, while the y-axis displays the risk on left side and the associated costs on right side.

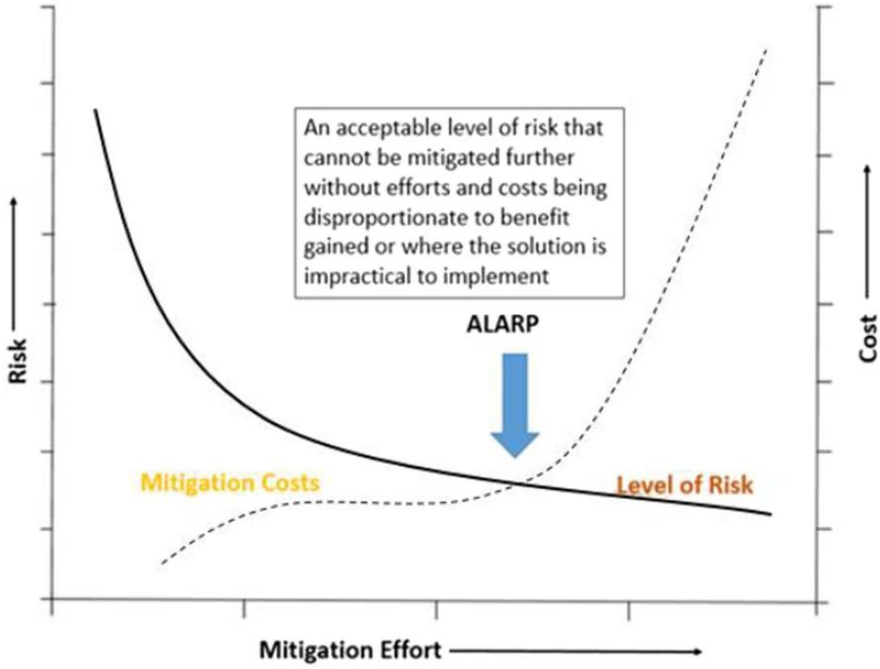

Figure 58 - Graph of ALARP principle for risk evaluation (Campbell et al., 2016; quoted by Sim et al., 2022).

So, two distinct curves appear – one representing the **mitigation costs** and the other denoting the **level of risk**. The mitigation costs curve unmistakably ascends as the mitigation effort increases. Concurrently, the level of risk descends until it intersects with the mitigation costs curve. This intersection, the point of convergence, represents the basis of the ALARP principle, as well as a compromise between two needs.

Nevertheless, as argued by Strouth and McDougall (2022), adopting ALARP as a default condition should be reconsidered, as it can be both unattainable and undesirable in numerous landslide risk management situations.

4.3 Risk mitigation: types of interventions

Rockfall mitigation measures are a critical component of geotechnical engineering and hazard management, aimed at minimizing the potential dangers posed by the abrupt release of rocks from steep slopes or cliffs.

These mitigation strategies encompass a diverse range of engineering, structural, and natural interventions, tailored to the specific characteristics of the site and the identified rockfall hazards.

The primary **objective** of rockfall mitigation is to enhance public safety, protect property, and maintain the functionality of transportation systems in areas prone to rockfall.

Various measures, both active and passive, were devised to either prevent rock detachment, control the trajectory of falling rocks, or provide protective measures for vulnerable areas. The **selection** of appropriate measures depends on factors such as the size of potential falling rocks, the frequency of events, and the accessibility of the site. Furthermore, a comprehensive approach often involves a combination of different measures to create a synergistic and effective defence against rockfall.

In the domain of rockfall protection, engineers encounter numerous **challenges**. Primarily, they confront the task of identifying **optimal locations** for the installation of protective structures. This determination relies on a comprehensive assessment of rock block sources, occurrence frequency, and anticipated trajectories derived from field surveys and meticulous data analysis. Engineers encounter a second challenge in determining the necessary protective **efficiency** for the design of the protective structure, that depends on the estimation of the rockfall kinetic energy. Then, another challenge is, of course, related to **financial constraints** (Kanno et al., 2023).

This chapter begins by exploring various rockfall risk mitigation measures, covering both **active** (stabilizing the rock) and **passive** (protecting against potential risks) strategies.

Then, a detailed explication of the specific mitigation measures tailored for the **Chianocco Gorge** case will be provided. Given the nature of this area as a tourist passage, paramount considerations will revolve around the necessity for implementing protective measures that are discreet and minimally visually intrusive, all the while maintaining safety as the foremost priority. Ensuring the safety of tourist paths will further entail the installation of handrails and warning signage.

4.3.1 Active interventions: stabilization

Proactively mitigating the risk of rockfall involves employing active measures to **prevent** the initial dislodgment of rock failures. Of course, for this kind of approach is fundamental to acquire meticulous geotechnical information, which consequently translates into **higher costs**. Nevertheless, the application of active remediation methods substantially decreases the likelihood of rockfall hazards.

Examples of these methods encompass rock scaling, the installation of rock bolts, the application of wire draped or anchored mesh (commonly known as rockfall netting), and the use of shotcrete.

The term rock **scaling** typically involves the controlled removal of unstable portions creating a stable slope geometry (Marchelli et al., 2023). Additionally, it encompasses the removal of scattered debris, as well as bushes and trees. This procedure entails eliminating precarious surface materials that pose a risk of rockfall.

As specified in Artusa website, rock scaling typically serves as the initial phase in all rock stabilization projects, creating a secure environment for subsequent actions like drilling or other necessary stabilization measures. Nevertheless, scaling can also function as an independent slope stabilization measure. In other words, scaling alone may suffice to stabilize certain slopes, whereas others may demand more comprehensive stabilization measures, including rock bolting, slope mesh netting, blasting, or shotcrete.

This measure can be performed by different ways. **Manual** rock scaling proves more effective than **mechanical** or demolition scaling since it targets individual rocks without compromising the stability of the entire slope. Alternatively, trim blasting can be utilized to eliminate larger rock features or masses. *Figure 59* shows an example of manual scaling performed by three operators, with the necessary safety measures in place.

Figure 59 - Three operators by performing rock scaling (from GeoStabilization International).

The process of rock **bolting** entails the insertion of steel bolts into rock formations, establishing a robust reinforcement system. This technique serves to prevent rockfalls, stabilize slopes, and enhance the overall structural integrity (from Utilities One, 2023).

The bolts work to secure potentially unstable jointed or fractured rock masses by applying compression, while **bearing faceplates** offer passive resistance. This results in the formation of a more stable structural entity (Nicholson, 2015). So, this solution aims to alter the mechanical properties of the joints, thereby consolidating the rock mass and binding it together (Marchelli et al., 2023).

Implementing rock bolting for rockfall prevention can also encounter various **challenges** and issues, including poor rock conditions, geological variability, installation difficulties, corrosion and maintenance, environmental impact and technical expertise requirements. Addressing these challenges requires careful planning, site-specific assessments, and continuous monitoring to adapt to changing conditions. It's essential to integrate rock bolting into a comprehensive rockfall mitigation strategy that may include complementary measures for enhanced effectiveness.

The **netting** system is another measure that can be considered active, as it acts directly on the rock face, with the aim of improving its stability. This kind of intervention is generally securely fastened to the slope using rock anchors (anchored mesh system). These **anchors** consist of steel rods embedded in grouted, narrow-diameter holes, meticulously drilled to specified depths in the rock.

The netting system is **flexible** enough to conform to the topography of the slope without altering the natural appearance significantly, and can be customized to deter shallow slides, mitigate deformations, and prevent the dislodging of rocks. In doing so, it serves as a protective barrier, safeguarding both life and property situated below.

On slopes with moderate inclines or areas featuring vegetation growth, it is advisable to position the mesh in close proximity to the slope. For extremely steep or nearly vertical slopes, securing the mesh at the cliff's top – while leaving the bottom open – facilitates the collection of rocks and debris in a trench at the slope's base. Critical to the stability of the system is the establishment of a secure and uninterrupted anchor point at the summit (from xrwiremesh, 2023).

An example of this system is shown in *figure 60*. Specifically, it is possible to note the presence of a larger mesh size and larger diameter wire, which serves as the main skeleton of the system and is capable of containing the larger rock blocks. Moreover, a reduced mesh size system is effective in managing rock block falls of a lesser dimension.

Certainly, the technical specifications – including diameter, mesh size, and anchor spacing – are contingent upon the specific characteristics of the case being assessed.

Figure 60 - An example of an active netting system (from Walcoom website).

An additional proactive measure to counteract rockfall involves the application of **shotcrete**. Shotcrete plays a significant role among various approaches to slope stabilization, owing to its adaptability, resilience, rapid strength development, and its ability to adhere firmly to the substrate. The substance is densely packed against the surface to seal cracks and fissures, inhibiting the release of loose materials.

It is crucial to emphasize that highly inclined slopes in areas characterized by subpar rock mass quality pose an elevated risk of slope failure. Consequently, merely applying a surface layer of shotcrete will be insufficient. Such slopes demand additional stabilization measures, including the implementation of wire, mesh, and fibers (from BestSupportUnderground website).

4.3.2 Passive interventions: protection

In cases where active measures are deemed impractical, passive alternatives can be employed to mitigate rockfall hazards.

The primary **goals** of this kind of measures include intercepting, diverting, absorbing, or containing falling rocks while minimizing the potential consequences of rockfall incidents. In other words, the aim is to prevent the impact of falling rocks on adjacent public spaces or infrastructure (elements at risk).

Generally, passive rockfall protection systems can be flexible type or rigid type. **Flexible** systems, such as rockfall nets and drapes, consist of steel or wire mesh sheets, cables, and anchors strategically positioned either over the surface or along the edge of the rock slope. **Rigid** systems like rockfall sheds and galleries are crafted from concrete or steel beams, columns, and slabs, strategically placed above roadways, railways, or buildings situated below or in proximity to the rock slope.

Embankments stand out as one of the most extensively employed rigid passive protection systems. These structures consist of layers of densely packed soil interspersed with geosynthetics, such as geogrids and geotextiles, strategically anchored to the external quarterdeck frame or encased around it (Oggeri et al., 2021).

Recognizing the paramount significance of this protection system, Oggeri et al. conducted numerous papers on the subject. These papers delve into intricate design details, comprehensive evaluation of full-scale tests, validation of the employed numerical models, and more.

For example, numerical model underwent scrutiny through attempts to replicate authentic conditions. So, various scenarios were simulated, involving diverse types of rock impacts on an embankment, encompassing variations in block velocities, energies, and geometric impact conditions. The **validation** process involved a meticulous comparison of the model's outcomes with data derived from the authors' practical experiences and **full-scale test** data compiled from pertinent literature sources. The outcomes of these efforts furnish valuable insights for designers and pertinent stakeholders in assessing the risk scenarios stemming from potential rock falls onto infrastructure (Oggeri et al., 2021).

The full-scale tests and the validation of the numerical model enables the formulation of a general **design** scheme. This framework serves as a guiding reference for selecting the specific characteristics of the protection embankment (Oggeri et al., 2009).

Anyway, selecting the appropriate passive measures against rockfall (a flexible or a rigid one) involves a nuanced consideration of factors, with the decision heavily influenced by the distinctive features of the rock slope and its surrounding environment.

The primary determinants guiding the choice of protective measures hinge predominantly on the **attributes of the slope**, coupled with the **frequency** and **magnitude** of rockfall events.

Notably, flexible systems are preferred for highly irregular slopes characterized by frequent but smaller rockfall incidents. They are effective in capturing and controlling smaller debris before it gains momentum.

On the contrary, rigid systems prove optimal for stable rocky slopes where the primary hazard arises from substantial boulders. Structures like sheds and tunnels, known for their robustness, form a formidable barrier, preventing rocks from reaching areas below that are susceptible to damage. Consequently, these rigid solutions are better suited for occurrences that are less frequent but may involve larger and more impactful rockfall events.

Determining factors in selecting the type of protective measures also include **cost** and **visual impact**. Flexible systems are generally more cost-effective and can be visually less obtrusive. They are often preferred in areas where minimizing the visual impact is important. On the other hand, rigid systems tend to be more expensive but offer a high level of protection. In some cases, particularly in urban or scenic areas, the appearance of rigid structures might be a consideration.

Space and **access constraints** can also be binding in this decision. Flexible systems can be more adaptable to limited space and access constraints due to their lighter weight and flexibility, while rigid ones require more planning and space for construction. They are suitable when ample space is available, and access is not a significant limitation.

Last but not least, it is fundamental to take into account **engineering** and **construction** considerations. In particular flexible measures are generally easier to install and may require less complex engineering, making them suitable for a range of slopes and locations. On the other hand, the rigid type systems demand careful engineering to ensure structural integrity, making them appropriate for specific sites where a more robust solution is necessary.

Ultimately, a comprehensive site assessment by engineers and geologists is crucial to determine the most suitable type of passive rockfall protection based on the unique characteristics and risks of the particular location.

Practically, passive remediation measures encompass the use of berms, rock traps (including ditches, barriers, catch fences, or mesh draping), and the implementation of rock sheds. Subsequent to providing a comprehensive overview of the two categories of passive protection systems, it is possible to argue that, among these, the most efficient methods generally are the rockfall **barriers** and **fences**, systems composed of steel or wire mesh panels, along with posts, cables, and anchors strategically installed along the base or contour of the rock slope.

The purpose of the aforementioned passive rockfall measures lies in establishing a **catchment area** with sufficient width and depth. Within this area, the kinetic energy of falling bodies is effectively dissipated. For concrete rockfall walls, the extent of the catchment area's “depth” is determined by the height of the wall (Pantelidis and Kokkalis, 2011).

4.4 Measures proposed in Chianocco

As noted earlier, the Chianocco Gorge case poses a risk due to the presence of sizable and **unstable boulders**. The instability of the blocks was identified through regular monitoring conducted by a mountain guide. Consequently, the Cottian Alps Protected Areas Management Authority, in March 2020, officially closed the pathway to Chianocco Gorge and the Via Ferrata, given its significance as a heavily frequented tourist area. In December 2022, the municipality of Chianocco secured funding to undertake safety measures, paving the way for the reopening of the site.

Engineer Casale's final-executive design proposes a comprehensive solution, incorporating the dislodging and abatement of smaller blocks, the consolidation of others through various methods, and the implementation of permanent monitoring for elements requiring heightened attention.

The primary challenge in situations like Chianocco lies in achieving safety standards through solutions that **minimize visible impact**. The paramount requirement is unquestionably to **guarantee the safety** of the site, even if a solution that is overly conspicuous could compromise the inherent beauty that this natural landscape long bestowed upon the community.

Balancing these two needs becomes crucial to ensure a safe and welcoming environment without compromising the inherent beauty of the mountain landscape.

As examined in the preceding chapters, the focal points for security measures predominantly involve the orographically right wall and the wall situated at the entrance of the Gorge. Specifically, the orographically right wall exhibits isolated individual blocks (*figure 61*), whereas the rock mass at the mouth of the Gorge is distinguished by conspicuous fractures spanning its full height, highlighting significant monoliths such as the renowned “Pillar” and “Hat” (*figure 62*).

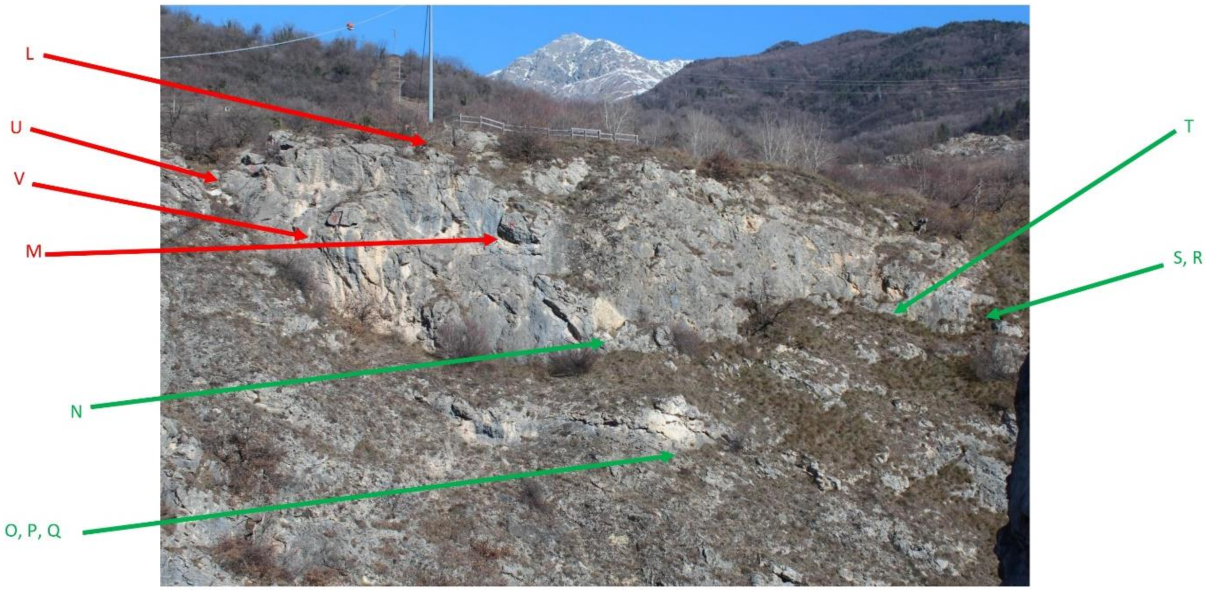

Figure 61 - Current measurement points on the wall in the orographic right (in green those no longer present).

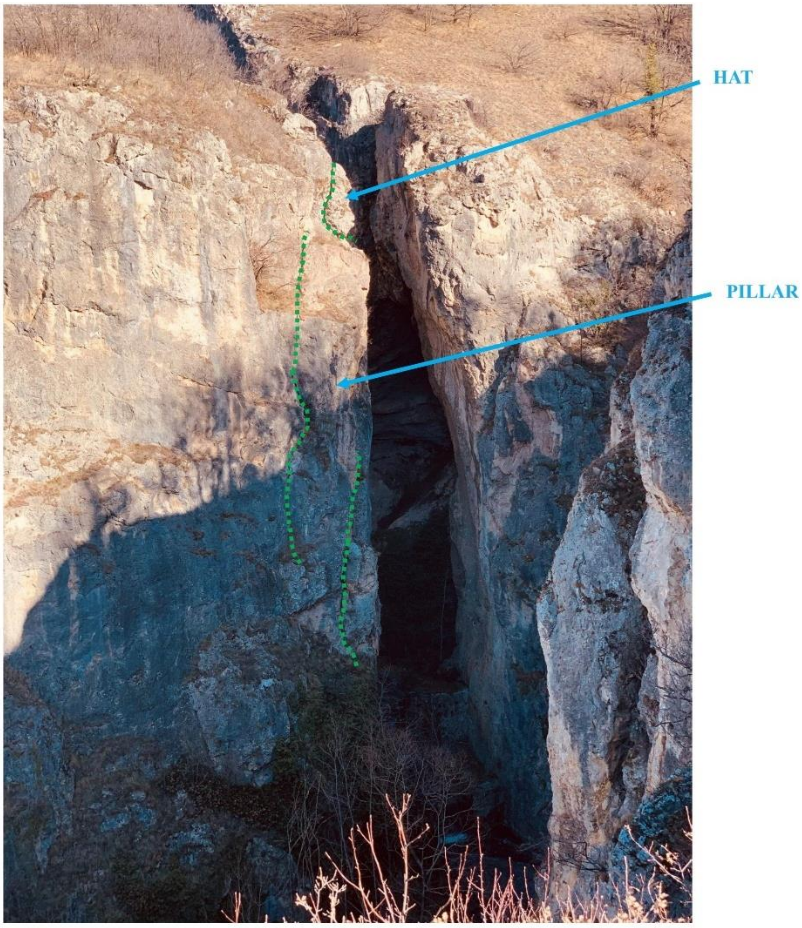

Figure 62 - Monolith at the mouth of the Gorge.

As outlined in Engineer Casale's project report, the existing **monitoring** is conducted manually approximately four times annually. It involves measuring the aperture of specific cracks that delineate the rock blocks, employing a **mechanical gauge** and referencing metal plates affixed to the ends of these cracks. The reported increase in the aperture of certain monitored fractures prompted the alert, leading to the subsequent closure of access to the Gorge.

However, although the current monitoring system provided useful assessment data, its suitability as a warning system is **limited** for several reasons (Casale). In fact, more frequent and closer monitoring measures are essential to manage the situation on a continuous basis. Furthermore, given the potential for sudden collapse, monitoring crack openings may prove ineffective in such scenarios. Finally, as the system relies on manual measurements, it is inherently susceptible to potential subjective errors. Subsequently, a dedicated chapter will explore various monitoring systems.

The suggested interventions explicitly consider the **operational intricacies** inherent in these environments, accounting for challenges arising from overhanging rocks and the presence of fragile infrastructure, such as the via ferrata.

In these locations, the additional inherent risk stems from the potential event necessitating the installation of protection, namely, the detachment of a rock block. "*It reveals that, additionally to operations, the environment itself constitutes one of the major sources of potential risks*" (Marchelli et al., 2023). This article published by Marchelli et al., specifically addressed safety concerns at construction sites of this nature by introducing a quantitative risk assessment method as a proposed solution. Additionally, it suggests specific safety policies aimed at mitigating potential risks.

Implementation of such designs typically demands **specialized contractors** with expertise in executing these methodologies, particularly in handling steep slopes where access may pose challenges.

Delving into the specifics of the **intervention proposals** outlined in Engineer Casale's project, it is suggested to conduct **scaling** operations on the smaller blocks located on the orographically right wall (M, U and V blocks). Hence, in situations like these that can be resolved through straightforward stabilization by scaling, the concern of visual impact does not arise. The scaling in this area also involves the manual extraction of minor debris. Similarly, the case applies to L-block situated on the same wall, even though necessitating a **rope sling**, which incurs minimal visual impact.

The recommended solution for the upper element at the mouth of the Gorge, previously referred to as the “Hat”, involves utilizing a sling with **constrained ropes** and **lateral anchors** secured into solid rock.

As anticipated, the “Pillar” block poses the greatest challenge in finding a solution that minimizes visual impact, given its substantial size. Two solutions were put forth for the “Pillar”.

The first, more visually impactful, entails a stabilizing intervention incorporating anchors and ropes.

The second option involves a hybrid system, combining the **stabilizing** approach with a continuous **monitoring** mechanism. The implementation of this system involves deploying four wire ropes, securely anchored laterally to the rock mass (*figure 63*). A notable feature of these ropes is the incorporation of **load cells**. Should there be any movement in the pillar, an increase in tension within the ropes is communicated to these load cells, enabling the potential activation of a real-time warning system.

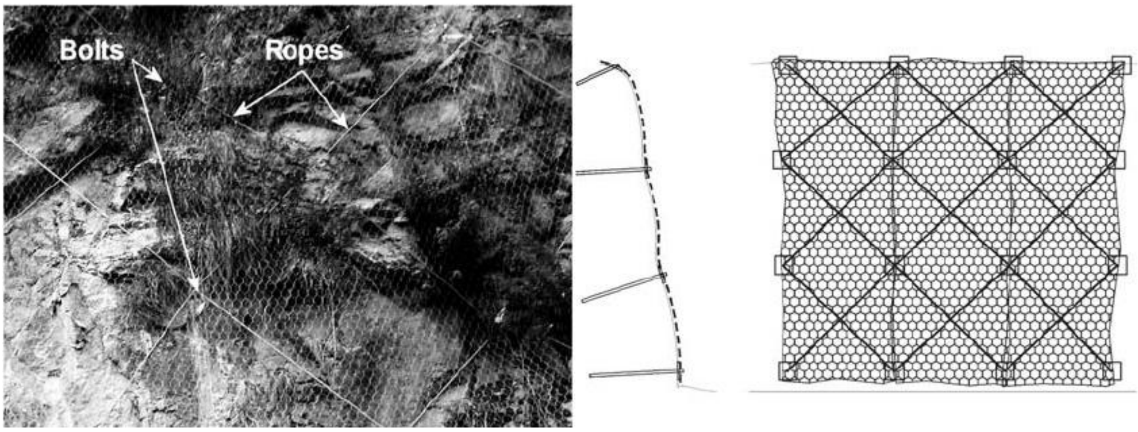

Figure 63 - Illustration of a drapery system designed to manage the dislodgment of rock fragments and enhance slope stability. Bolts length must be greater than fractured or destressed zone to ensure proper anchoring to drapery system (Oggeri et al., 2009).

Moreover, the implementation of **displacement sensors** spanning the fractures will not only prevent false alarms but also enhance the precision of the system.

Another fundamental monitoring will be conducted by two **temperature sensors**. As mentioned earlier, variations in temperature can impact rockfall occurrences. Hence, a minimum one-year observation period was suggested to establish threshold values. Exceeding these values would activate an alarm system.

In addition, manual monitoring would be superseded by an **aerial topographic monitoring system**, offering increased reliability by minimizing subjective errors.

Finally, it should not be forgotten that since this is an area with a high tourist presence, measures are necessary to allow safe use of the trails and areas of the site of interest. Indeed, in mountainous areas, especially along **tourist routes**, the implementation of safety measures such as handrails and signage for wet or slippery surfaces plays an indispensable role in ensuring the safety of visitors.

The typical environmental and topographical conditions of such areas, often characterized by rugged terrain and climate variations, can create potentially dangerous situations. The presence of **handrails** on trails or exposed passages helps provide physical support to hikers, helping them maintain balance in rough terrain.

At the same time, clear and appropriate **signage** warns tourists of potential hazards, such as wet or slippery surfaces, enabling them to take appropriate precautions during their journey. In this way, such measures not only improve the overall safety of mountain areas, but also help promote a more conscious and enjoyable tourist experience.

To resume, based on the site's characteristics, the type of landslide, and the socio-economic conditions, various potential mitigation interventions can be identified. The selection of the most suitable intervention is determined through the execution of **residual risk** calculations and a comprehensive **cost-benefit** analysis.

Indeed, every mitigation intervention results in a reduction in risk represented by a ΔR, and the remaining risk is essentially the residual risk (R_r). As a result, the approach yielding the lowest residual risk is the most conservative, but also the most expensive.

This concept underscores the significance and potential of risk assessment as a valuable decision support tool (Frattini and Crosta, 2006).

Last but not least, despite the amalgamation of different interventions will effectively reduce the current risk, continuous monitoring and periodic reassessment are imperative to guarantee the sustained effectiveness of the mitigation measures over time.

Indeed, an important aspect in rockfall risk management is represented by both the **aging** and **degradation** processes affecting the installed protection devices during their working life (Howald et al., 2017; quoted by Scavia et al., 2020), that inevitably leads to a decrease in effectiveness and thus a change in risk level.

The **effectiveness** of rockfall protection measures, reflected in their behaviour and performance over time, are subject to diverse and unpredictable factors. These include time-dependent elements such as impacts and interactions with vegetation, coupled with the critical role of maintenance – be it incorrect or entirely neglected. The assessment of the degree of conservation is, therefore, of paramount importance for the effective management of rockfall protection systems.

As a result, the role of **maintenance** becomes crucial for public administrators when evaluating the duration for which a particular investment guarantees the necessary risk mitigation (Scavia et al., 2020).

5. Monitoring and warning systems

5.1 Introduction

As mentioned in the previous paragraphs, the **growing risks of landslides** can be attributed to intensified developments in susceptible terrains, construction activities, climate change, deforestation, and other contributing factors.

Nevertheless, implementing an **advanced technology** of warning system, alongside precise prediction capabilities, can effectively mitigate and manage landslides, substantially reducing damage and providing a crucial means of control and prevention amid escalating threats. So, it is imperative to persist in the development of tools and techniques for the detection and monitoring of these gravitational slope processes.

As argued by Ponziani et al. (2023), advancements in these methods are crucial for enhancing our understanding and response to landslides, ultimately contributing to more effective risk management strategies.

An essential point to highlight is that, in hazard mitigation, monitoring does not operate as an active measure in physical sense, but rather acts as a risk control function. Fundamentally, the monitoring system manages the concept of the "factor of recurrence", concerning the potential initiation of an event.

This chapter provides an overview of the primary components and key aspects of a monitoring system, offering essential insights into their functionality.

Following that, a subsection is dedicated to LEWS, highlighting their ability to transmit real-time signals, thereby emphasizing their necessity in high-risk situations. Additionally, their potential economic benefits are also discussed.

In conclusion, proposals for monitoring and warning systems specific to the Chianocco case are outlined.

5.2 How a monitoring system works

5.2.1 Main components

Monitoring systems comprise a **field unit** and a **remote network interface**. The field system incorporates primary sensors to monitor landslide movements (Prakasam et al., 2021).

Sensor devices play a pivotal role in the system and are strategically installed in contact with the structure under observation. The types of sensors employed vary, aligning with the specific physical variables they measure, such as tilt, force, humidity, and others.

Diverse array of sensors exists, and this ensures a comprehensive approach to capturing and analysing crucial data for effective monitoring of the targeted system or structure. Certainly, among the various critical attributes, as elaborated further below, precision stands out as a key feature influencing the device's capabilities and, of course, the corresponding price.

Linked to the sensors are the acquisition unit and transducer device. The connection can be established either through electrical cables or wirelessly (depending on the distance to be covered and the type of sensor). The **acquisition unit** is responsible for collecting data, while the **transducer** converts these data it into an electrical signal, which are then read by a software.

The acquisition system is linked to a **modem** that facilitates the transmission of acquired data to a remote device, such as a PC situated in a control station.

At this point, specialized **software** is required to manage and process the received data. In situations where there is an elevated risk, it becomes essential to set tolerance thresholds within the software and in such scenarios, the system will be equipped with an alarm dissemination mechanism.

So, the thresholds set in the software allow for the activation of an **alarm** signal whenever they are surpassed, enabling timely responses in critical situations. The alarm signal may take various forms, such as a light, a siren, a message or alert on cell phone, a traffic light, and so forth.

5.2.2 Key aspects

After delineating the principal components of a monitoring system, the focus can now shift towards the main operational aspects.

Generally speaking, a monitoring system is configured as a device capable of performing, in a periodic and repeated manner over time, the detection of a specific physical parameter, ensuring a high level of precision and accuracy. From this sentence, it is possible to extrapolate the **key aspects** of such systems which include (i) the *physical variable* subject to measurement, (ii) the *sampling rate*, and (iii) the *reliability* and *accuracy* of the measurement.

Concerning landslides, the monitoring system encompasses a range of **physical variables** that can be systematically measured. This comprehensive set, detailed in the *figure* 64, includes assessments of surface and/or subsurface movements, geophysical measurements, meteorological parameters, and factors associated with water presence.

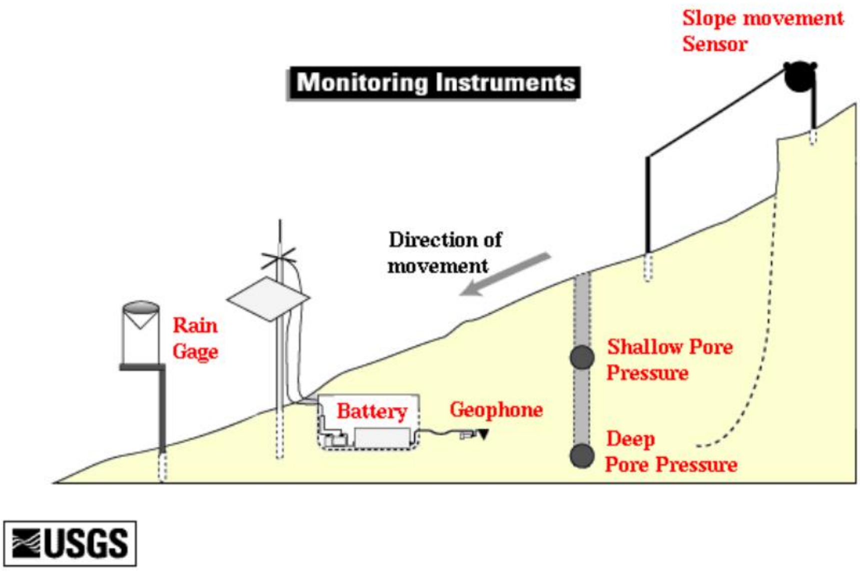

Figure 64 – General example representing the different parameters that can be monitored (from USGS).

Another critical component of a monitoring system is the **acquisition frequency**, whose choice depends mainly on the specific landslide under observation. Indeed, the adequacy of a monitoring system hinges on aligning the acquisition frequency with the speed of the landslide's evolution. Otherwise, such it would fail to provide an accurate representation of the ongoing events.

However, the obtained results' quality relies not only on the acquisition frequency, but also on factors concerning the **transfer** and **processing** of the acquired data, aspects that cannot be overlooked.

Based on these considerations, it is possible to delineate the categorization of monitoring systems into three distinct types:

- **low-frequency systems**, characterized by extended data processing times, deliver multi-time analyses on a monthly or annual basis;
- **near-real time systems;**
- **real-time systems**, distinguished by their extremely high-frequency acquisition, enabling nearly instantaneous data provision. These systems are employed in scenarios characterized by extreme and high-speed events, often complemented by alarm systems.

These last two types of systems, with high acquisition frequencies, can be used to trigger warning and alarm functions, technically defined as *early warning*.

Timely and dynamic monitoring of deformation, coupled with early warning information, can significantly mitigate the risk of casualties caused by landslides (Shruti et al., 2018; quoted by Wang et al., 2022).

Before delving into a more-in-depth analysis of landslide early warning systems (LEWS), it is imperative to highlight a fundamental aspect of monitoring systems. For optimal functionality, the **licensing** of most monitoring systems typically requires a minimum of two complete seasonal cycles.

Indeed, understanding the variations in the monitored physical parameter is valuable not only in relation to the passage of time but also considering its response to specific events, such as weather phenomena, earthquakes, fires etc.

5.3 Landslide early warning systems (LEWS)

As for the United Nations International Strategy for Disaster Reduction (UNISDR 2009) definition, an *early warning system* is described as the collection of capabilities necessary for producing and transmitting timely and relevant warning information.

Its purpose is to empower individuals, communities, and organizations facing a hazard to prepare and respond adequately within a significant timeframe, thereby minimizing the potential for harm or loss (Wu et al., 2019).

LEWS can be formulated and applied at two distinct scales: systems focusing on individual landslides at the slope scale can be termed as local (Lo-LEWS); systems operating over extensive areas at the regional scale are denoted as territorial systems (Te-LEWS) (Piciullo et al., 2018).

The effectiveness of an Early Warning System (EWS) is contingent upon the capability to identify and to monitor in real-time specific and crucial **indicators**, referred to as precursors (Barla and Antolini, 2016).

Early Warning Systems (EWSs) offer significant **economic benefits** by reducing damage and losses, streamlining cost-effective planning and response initiatives, safeguarding economic activities, and lowering costs in emergency response operations (Rogers and Tsirkunov, 2011; Grasso, 2014).

The creation of cost-effective early warning systems holds utmost significance for the real-time monitoring of natural hazards, such as landslides (Prakasam et al., 2021).

The economic benefits mentioned above render **investing in LEWS** a judicious decision. Anyway, it's essential to acknowledge that the expenses associated with implementing LEWS can fluctuate significantly, influenced by factors such as the size and complexity of the monitored area, the technology and infrastructure utilized, and the degree of system sophistication.

On that account, gauging the costs and benefits of deploying local LEWS remains a **complex task**. Furthermore, to the authors' knowledge, the estimated cost of the monitoring instrumentation for local and site-specific LEWS is currently unknown or unpublished and this information is fundamental for policymakers engaged in disaster risk reduction efforts. (Sapena et al., 2023).

So, as pointed out by Sapena et al. (2023), LEWS present significant potential when integrated and managed effectively, but they also encounter various **challenges**: the monitoring components within LEWS frequently depend on **costly**, advanced sensor systems; these systems necessitate highly **skilled personnel** for operation and are intricately customized to the **local context**, posing challenges for their seamless transfer to different regions or countries.

Certainly, as mentioned earlier, for a strategic and effective implementation, it is imperative to conduct a thorough study aimed to identify highly exposed landslides **prone areas**, coupled with a comprehensive **cost analysis**.

The early warning systems make use of thresholds, where a "**threshold**" denotes the minimum or maximum level of a quantity required for a process to occur or for a state to undergo a change (White et al., 1996; quoted by Guzzetti et al., 2019).
The difficulty in embracing this approach stems from the task of establishing the values for thresholds, essential for delineating various levels of criticality. This challenge arises from the restricted understanding of the specific landslide phenomenon.

Empirical, **statistical**, or **physically** based methodologies can be employed to establish thresholds (Guzzetti et al., 2019).

Certainly, the selection of the method to establish thresholds varies depending on the phenomenon under observation. For instance, in the context of Chianocco Gorge, the most suitable approach is the **physically based**, given its correlation with a tangible displacement that could trigger the destabilization of the blockade. In scenarios involving more recurrent phenomena, such as floods or widespread landslides, empirical and statistical methods are typically favoured.

In addition, two threshold values are generally established: a **warning** value and an **alarm** value. If exceeded, the first signals to pay attention, and the other one, generally prompts the closure of the monitored site.

Lastly, it's crucial to emphasize that the effectiveness of these systems relies not only on technical factors like lead time (time lapse between the issuance of a warning and the onset of the predicted landslide event), alert dissemination, and emergency response plans but also on **social considerations**.

These factors encompass public response and education. Indeed, if individuals are not adequately informed during a warning event, their reaction may not align with the expectations of system managers (Pecoraro et al., 2018).

So, in developing and overseeing a Landslide Early Warning System (LEWS) for optimal efficiency and effectiveness, it is fundamental to tackle an array of considerations. Neglecting or underestimating any component within the system could result in the failure of the entire system.

Monitoring strategies, encompassing monitored parameters and monitoring methods, assume a pivotal role in both the design and operational phases of a LEWS (Pecoraro et al., 2018).

5.4 Monitoring systems proposed in Chianocco

When selecting monitoring and warning systems, as with any mitigation measure, the decision is contingent upon the specific location in question. This entails a comprehensive evaluation of the requirements and economic feasibility associated with the chosen system.

In the case of Chianocco Gorge, as highlighted by Engineer Casale in the general report, the existing monitoring system turns out to be inadequate for functioning as an alert system. Notably, it lacks the capability to provide measurements in close temporal proximity, and furthermore, it is susceptible to subjective errors associated with the manner in which measurements are executed.

For these reasons, the proposed intervention incorporates **real time monitoring**, executed through different sensors, like **load cells** (*figure 65*), transducers capable of converting force into a measurable electrical output. Its functionality is contingent upon being coupled with external sensors like strain gauges. In this case, load cells are integrated to a four belting **wire rope** system, securely anchored to the rock mass.

This system will enable real-time alert activation. Indeed, in the event of movement, the load will exert pressure on the belting ropes, causing an increase in tension that will be detected by the load cells, triggering the alert mechanism.

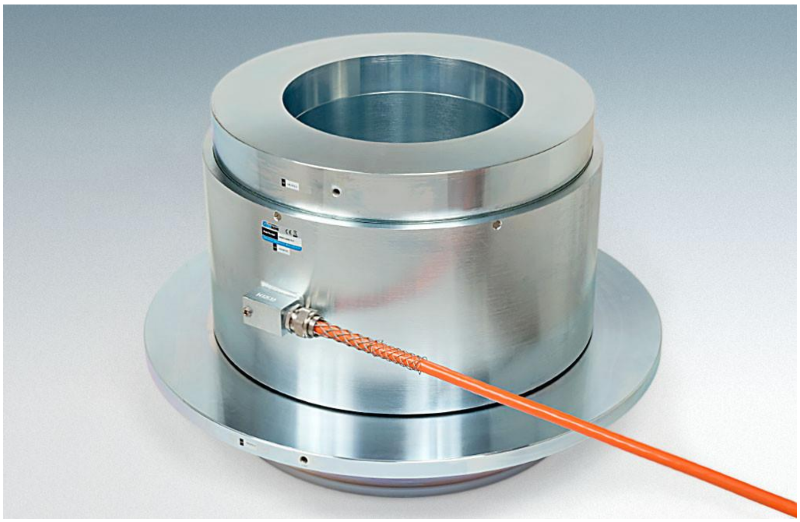

Figure 65 - An example of 1500 Ton Load Cells (VW) (from GEOKON).

Furthermore, in conjunction with the load cells, the inclusion of **displacement sensors** along the fractures is imperative to prevent false alarms in the system.

Additional devices contributing to the enhanced accuracy of monitoring include **temperature sensors** (*figure 66*) in proximity to the joints to be monitored. These sensors are strategically placed in various environmental conditions, including areas exposed to sunlight and shaded locations.

Figure 66 – Example of pressurized water-tight encapsulated sensors employed for measuring temperature in the ground, rock, or on the structure (from SOLEXPERTS).

Other sensor devices suitable for this case study include, for instance:

- **Tiltmeters**, affixed to the wall (like in *figure 67*), are designed to detect lateral movement, facilitated by accelerometers capable of sensing lateral imbalance concerning an axial reference.
- **Topographic prisms** or **targets**, affixed to a cemented bolt, is adept at materializing coordinates with precision (*figure 68*).
- **Laser scanner** or **LiDAR** (*figure 69*), already mentioned in chapter concerning the block volume estimation, proves invaluable in situations like this, enabling a comprehensive survey of the entire surface within just a few hours.
- **Weather stations** (*figure 70*), located near the site of interest, enabling the acquisition of atmospheric parameters, including pressure, relative humidity, and temperature.

The selection of the most suitable monitoring instruments should be based on a set of criteria, including simplicity, robustness, reliability, and cost-effectiveness (Pecoraro et al., 2018).

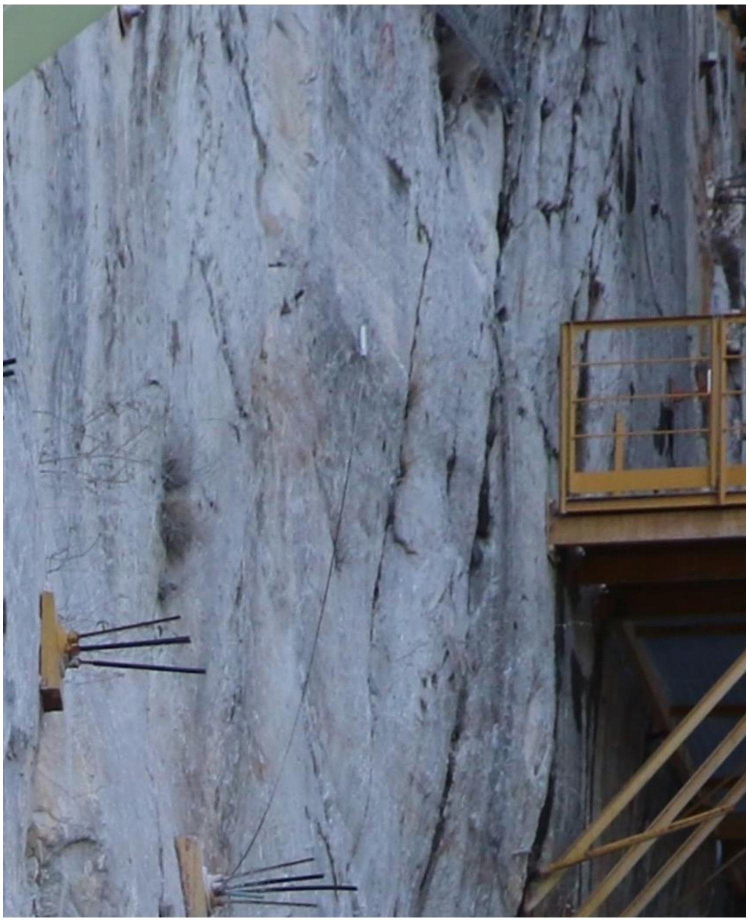

Figure 67 - Tiltmeter in vertical wall in underground marble quarry (Oggeri).

Figure 68 - A topographic target mounted on a rock mass (from SISGEO).

Figure 69 - LiDAR device (courtesy of Cina A.).

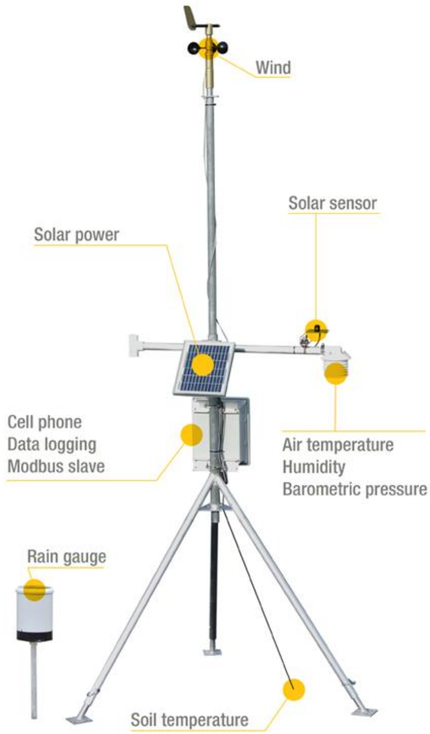

Figure 70 - Weather station solution by DYACON. The incorporated sensors gauge wind speeds, air temperature and pressure, humidity levels, soil temperature and moisture, as well as rainfall levels.

Beyond these sensors, implementing **aerial topographic control** (*figure 71*) of the investigated area will contribute to minimizing subjective errors associated with manual monitoring.

Figure 71 - Drone and camera utilized for aerial photogrammetry survey (courtesy of Maschio P.).

Of course, considering the low population density in the area, a traffic light system could suffice as an **alarm signal** to regulate and control access through the danger zone. Anyway, in instances of elevated risk, such as during days of heavy rainfall, it is prudent to proactively close the site, even in the hours following the event.

So, integrating various sensors and control systems constitutes an effective strategy for mitigating the risks inherent in areas susceptible to phenomena like landslides. The aforementioned measures prove to be adequate in facilitating decision-making processes regarding the opening or closing of access to the tourist site.

Last but not least, it is unequivocally crucial to incorporate a comprehensive **maintenance plan** to guarantee the sustained, long-term operation of the installed systems.

6. Discussion and conclusion

This thesis undertook a comprehensive analysis of recurring themes in the realm of environmental engineering. Key topics explored included the study of erosional events leading to gorge formation, the diverse manifestations of rock failure, risk assessment about landslide events, and the selection of appropriate mitigation measures.

To do this, a parallel analysis of a specific case was conducted, that of the Chianocco Gorge, a place with a high risk of rockfall events. Following anomalous observations, the site was pre-emptively closed (in March 2020). Subsequently, efforts were directed towards the development of a project aimed at ensuring the safety of the various tourist routes that traverse the gorge.

The challenge in situations of this nature resides in identifying solutions that ensure the **stability** of the rocks without compromising the visual **aesthetics** of the surroundings.

For smaller blocks, the implementation of the scaling technique was recommended. The "Hat" block solution entailed the utilization of constrained ropes and lateral anchors firmly secured into solid rock.

Ultimately, the most significant challenges were evident with the larger block situated at the mouth of the gorge, referred to as "Pillar". In this instance, proposing solutions devoid of visual impact proved unfeasible. However, through the implementation of **continuous monitoring**, it became possible to mitigate the impact significantly. The most viable solution, as advocated by Engineer Casale, involved the utilization of four wire ropes firmly anchored laterally to the rock mass. These ropes were equipped with load cells. Furthermore, the inclusion of displacement and temperature sensors served to enhance the precision and efficacy of the system.

Additional challenges arose in the execution of mitigation measures, encompassing both the design and implementation phases.

During the design phase, the provision of accurate input data is considered crucial for the efficacy of the chosen system. Consequently, a dedicated chapter was included to address methods for **estimating the volume** of rock blocks.

Specifically, the issue of joints **persistence** concerning volume estimation was thoroughly explored. In the past, sometimes was not given the right consideration to this feature, and the discontinuities were, for simplicity, considered as entirely persistent, significantly impacting the assessment of rock volume susceptible to detachment. Anyway, the integration of diverse traditional methodologies from existing literature with cutting-edge modern technologies emerged as the most dependable solution.

The challenges associated with the implementation of the chosen measures were prominently linked to the requirement for **highly skilled personnel** in these operations, consequently resulting in **elevated costs**. This poses a significant constraint on achieving economic feasibility.

Furthermore, despite the robustness of the security measures, the **temporary closure** of the site in adverse weather conditions underlined the delicacy and the need to adopt a holistic approach to ensure the safety and long-term sustainability of the Chianocco Gorge.

The overarching challenge lies in the absence of standardized guidelines for designing these mitigation works. Each case stands unique, demanding preliminary studies that are essential for a comprehensive understanding of the specific circumstances. This emphasizes the need for a tailored approach, acknowledging the distinct characteristics of each situation before formulating effective mitigation strategies. In the intricate landscape of environmental engineering, where nature presents diverse and complex scenarios, the importance of individualized study and consideration becomes paramount.

This thesis afforded me the opportunity to deepen my understanding of a particular case susceptible to landslide risk through a comprehensive analysis of its various components. I contend that in an era marked by frequent extreme weather occurrences, it becomes imperative for research to continuously progress in enhancing monitoring and alert technology. Such advancements are crucial for proactively addressing and mitigating the impact of any adverse events.

Moreover, it is fundamental to underscore the significance of ensuring the safety of tourist routes, particularly in mountainous areas. This emphasizes the necessity for proper signage, handrails, supports, and the presence of qualified personnel, especially on days of high attendance.

Of course, the risk factors associated with frequenting tourist trails are intricately linked to user education and **awareness** of the natural conditions of these paths. These are not mere amusement parks; instead, they are areas where individuals must possess a personal “sense” of what they are undertaking. Understanding and **respecting** the environment become imperative, emphasizing that these trails demand a heightened level of responsibility from those who traverse them.

The constrained economic resources allocated for managing these routes, without resorting to entrance fees like those implemented for the Gorges de la Diosaz, underscore the necessity for consistent inspection and surveillance. To address potential challenges, it becomes essential to implement passive interventions – measures not reliant on user actions – to effectively contain and mitigate major situations.

In summary, I assert that the amalgamation of these considerations and techniques – ranging from active measures to preventive approaches – paves the way for a more secure utilization of mountainous territories. Such an approach, in fact, is able to ensures the preservation of the awe-inspiring landscapes, providing tourists and sports enthusiasts with remarkable and as safe as possible experiences.

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