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Blasting of Unstable Rock Elements on Steep Slopes

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Abstract: The improvement of safety conditions on hazardous rock slopes in civil work, mining and quarrying, and urban environments can be achieved through the use of explosives for the removal of unstable rock elements and final profiling. This technique is often applied because, in most cases, drill and blast operations, where they can be used, are cheaper and faster than other techniques and require fewer subsequent maintenance interventions. Blasting represents a suitable and effective solution in terms of different geometries, rock formation types, access to site, safety, and the long-term durability of results. The primary purpose of this approach is the improvement of the safety conditions of sites, depending on their local features, as well as the safety of workers, so that the blasting scheme, geometry, and firing can be carefully adapted, thus imposing relevant limitations on the operating techniques. All these constraints associated with complex logistics make it difficult to standardize the demolition technique, due to different situations in terms of extension, location, fracturing state, and associated traffic risk. Considering the significant number of influencing factors for both the rock mass features and for the topography, the present research has been necessarily validated through the analysis of several case histories, thus on an experiential basis focusing on some simple control parameters to help engineers and practitioners regarding the first design and control of blasting schemes.

Keywords: blasting; slope protection; natural hazards; powder factor; rockfall; explosive

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1. Introduction

Unstable rock elements along a slope pose significant hazards linked to the possibility of rockfalls. Managing these situations becomes crucial to ensure safety for nearby infrastructure, communities, and the environment, reducing the risk of rockfalls by eliminating potential sources of instability. The simplest method for addressing unstable rock elements on slopes is "rock scaling", or simply "scaling". To address these challenges effectively, this research focuses on using blasting techniques to improve slope safety conditions by removing unstable rock blocks. Unlike traditional scaling, which is carried out by climbers using portable devices, this method uses carefully designed drill and blast operations tailored to complex geometries and conditions where conventional methods may be less effective. The main limitation of the common scaling along slopes is that it is time-consuming for the workers operating in difficult conditions and does not have the ability to cover large volumes, while it is decisive for the final cleaning of residual small fragments after blasting or demolition. A common feature and requirement among operative methods is that of claiming skilled personnel, for safety and also for care in preparation of the site in terms of access, equipment, and control.

By analyzing multiple blasting cases, this study develops a simplified approach to determine the Powder Factor (PF), which can serve as both a design validation tool and a cost estimation parameter for interventions on unstable slopes. Using explosives to remove unstable rock elements can be an effective technique for improving safety conditions on unstable rock slopes. The use of explosives can quickly break up large volumes of rock, making the removal process faster compared to manual or mechanical methods. This efficiency is especially beneficial for addressing urgent safety concerns on unstable slopes.

Further, drill and blast operations, which utilize explosives, are often more cost-effective than other techniques. While upfront costs are associated with explosives and drilling equipment, the overall project costs may be lower due to reduced time, labor, and equipment usage. In comparison, other techniques can be adopted, such as hydraulic splitting, chemical rock breaking, expansive grout, and quick reactive powder; each solution can exhibit its own advantages in terms of safety, environmental suitability, or vibration reduction, but geometrical precision of cutting and rock fragmentation control are the key factors for conventional blasting agents (both as cartridges and also as detonating cords).

Blasting can target specific areas of instability, minimizing disruption to surrounding areas and infrastructure. This technique can be tailored to suit the site's specific geological conditions and requirements. Depending on the situation, different types of explosives and blasting methods can be adopted to achieve desired outcomes, such as controlled fragmentation or controlled collapse.

Compared to some alternative methods, such as rock bolting or slope reinforcement, drill and blast operations may require less subsequent maintenance interventions. Once unstable rock elements are removed, ongoing monitoring and maintenance efforts may be reduced, leading to long-term cost savings.

However, it is essential to note that the use of explosives for slope stabilization should be carefully planned and executed to ensure safety and minimize environmental impact. This includes conducting thorough site assessments, risk analyses, and blast designs, and implementing strict safety measures throughout the drilling and blasting process [1]. Additionally, environmental regulations and community concerns must be taken into account to mitigate any potential adverse effects.

While explosives can offer significant advantages in certain situations, they are not always the most suitable solution for every slope stabilization project. Alternative methods, such as slope reinforcement, may be more suitable depending on the site's specific circumstances. It is essential to consider all available options and consult experienced professionals to determine the most effective approach for improving safety conditions on unstable rock slopes.

When addressing unstable rock elements on slopes, it is essential to conduct thorough site assessments, consider the underlying geology and hydrology, and prioritize safety at all times. Implementing a combination of stabilization measures tailored to the specific site conditions can help mitigate risks and ensure the long-term stability of the slope.

In a simplified approach, it should be possible to design ordinary blasting and controlled blasting. Ordinary blasting works for tunnel excavation, quarry production, etc., and is associated with well-coded parameters as result of many experiences over the years, depending on the available techniques and results obtained. These parameters are mainly geometrics (blasthole diameter, blasthole depth, spacing, burden, etc.), but there is a synthetic parameter that reflects the characteristics of the blasting, the rock features, and the fragmentation to be obtained, which is the powder factor (PF), which can be defined as the weight of explosives used (in kilograms) per broken rock volume (in cubic meters) [2]. Generally, the PF is a crucial parameter in blasting design, as it helps to determine the amount of explosive needed to efficiently break the rock while minimizing waste and controlling the fragmentation size. A higher PF generally results in more energy being applied to the rock, which can lead to larger fragmentation and better productivity in some cases. However, excessive powder factors can lead to overbreak, increased vibration, and environmental concerns. The optimal PF depends on various factors such as the rock type, geology, desired fragmentation, environmental considerations, and safety requirements. The PF can be estimated and adjusted based on these factors to achieve the desired results with minimal adverse effects. Controlled blasting techniques aim to take great care of the resulting profile, to avoid damage to rock surfaces left in place, and to minimize induced vibrations; they are used to efficiently distribute explosive charge in the rock mass volume, thereby minimizing the fracturing of rock beyond the crestline of the highwall or designed boundary of main excavation zones.

The value of the PF hinges significantly on the presence or absence of free surfaces that facilitate the blasting process. Rock blasting leads to volume expansion. When a free surface is available, this volume increase can dissipate outward. Otherwise, in scenarios lacking a free surface, additional energy is required to displace the broken material and create space for the material blasted sequentially by a series of micro-delayed mines.

This fundamental principle underscores why, as a rule, a blind tunnel excavation typically yields shows higher PF values compared to a stepped quarry configuration [1]. In the latter, where a free surface extends for the entire height of each step, the possibility of material displacement is notably enhanced. In standard geometric situations, the PF has become a synthetic control parameter indicative of the accuracy of the blasting design.

In more complex cases, where the geometry is irregular and the presence of free surfaces varies from case to case, it is much more difficult to standardize the PF and then use it as a control parameter. Typically, the demolition of unstable blocks on a slope reflects this last situation, with shapes, positions, geological and structural characteristics, and free surfaces being extremely variable from case to case. Blasting for isolated rock elements differs significantly from other projects, such as quarry or tunnel blasting, due to its focus on minimizing collateral damage and ensuring post-blast stability. These operations prioritize precise detachment over fragmentation, requiring tailored designs that account for irregular geometries, limited free surfaces, and environmental constraints. Unlike bulk fragmentation, the goal here is often safe displacement rather than maximizing yield or productivity.

This research, which is focused on novel features, proposes a first procedure to determine in advance the PF related to the demolition of unstable rock blocks in complex situations by proposing a simplified approach. In this way, the PF can be used to quickly check the correct blasting design and to estimate the intervention costs in advance.

The study has been carried out by analyzing several blasting cases across different contexts and scenarios. These cases serve as the basis for determining how PF varies in response to changes in blasting conditions. Through this analysis, the authors aim to elucidate the relationship between PF and the various factors influencing the blasting design.

2. Materials and Methods

2.1. Experimental Approach to Powder Factor (PF)

Several approaches have been developed for estimating the PF in tunnel blasting and in open-air bench blasting, but not for the blasting of a single element on a slope. The PF permits summarizing information in a single parameter, even if in a very simplified way; it captures several conditions of the blasting pattern and provides an estimation regarding the blasting efficiency. Many contributions are available in the technical literature seeking correlations between PF and induced vibration, fragment size distribution, residual contour [3], and stability; as an example, key objectives in the drilling and blasting design are the determination of the powder factor, as well as the explosive weight and distribution in rock mass [4]; other studies examine the improvement of the blasting design for a more satisfying fragmentation, a more tolerable oversized fragments rate in relation to the overall blasted rock volume, and better bench stability [5–7], as well as the adoption of numerical methods for the quantitative assessment of the effectiveness of vibration reduction in line-drilling as a screening approach [8]. Interdependent factors should be studied by careful monitoring during field tests; fragmentation and environmental effects are influenced by the amount of powder factor; a higher amount of powder factor improves fragmentation and, thus, productivity—the blast-induced vibration and air-blast also rise with an increase in the powder factor. This impasse calls for an optimum powder factor for sustainable blasting operations [9]. Finally, effective parameters that influence the powder factor can be divided into three contributions, namely, rock mass, geometric, and explosive parameters [10].

Referring to the specific technical literature, [11] states regarding tunnel blasting that the PF depends on the blasting section, rock type, explosive type, and blasting pattern. The blasting section is the most relevant parameter and the PF can be estimated as follows:

$$\mathrm{PF} = \mathrm{A} * \mathrm{B} * \mathrm{C} * [(10/\mathrm{S}) + 0.6] \tag{1}$$

where

- A is a coefficient that varies according to the rock type;
- B depends on the employed explosive type;
- C is related to the blasting pattern adopted;
- S is the area of the excavation section.

A, B, and C were tabulated based on the analysis of several real cases.

More generally, referring to the existing formulas for the dimensioning of explosive charges, according to empirical study, these formulas include the following [12]:

- A coefficient characteristic of the rock to be blasted;
- A coefficient characteristic of the employed explosive;
- A coefficient of "effect" referring to the result to be obtained with the blasting (size distribution of the blasted material, width of the zone of influence of the charge);
- A characteristic dimension of the blasting pattern geometry (normally, the line of least resistance), eventually raised to a power, or a polynomial combination of several characteristic dimensions.

The more general expression of such formulas may be written as follows:

$$\mathrm{C} = \mathrm{k}' * \mathrm{k}'' * \mathrm{k}''' * \mathrm{f(I)} \tag{2}$$

where

- C is the explosive charge;
- k' represents a coefficient referring to the rock type;
- k'' depends on the employed explosive type;
- k''' is the "effect" coefficient for fragmentation;
- I is the characteristic dimension of the rock block to be blasted;
- f(I) is a function of "I" raised to a power of a number varying from 2 to 3, with lower values associated with blasting along a defined failure surface and higher values referring to blasting volume.

When the exponent of f(I) is 2, Equation (2) refers to a simple detachment effect, mainly based on the tensile strength of the rock. When, instead, the exponent is 3, (2) refers to a volume to be blasted.

As was to be expected, in the first case, C is much smaller than in the second case.

The study was carried out through an in-depth analysis of numerous real-world blasting cases, aiming to discern and extrapolate the key factors governing the powder factor. By meticulously examining these cases, we seek to unveil the intricate interplay of various elements influencing the efficiency and efficacy of blasting operations.

Through careful observation and analysis, patterns began to emerge, shedding light on the nuanced factors that dictate the PF in blasting. Factors such as rock type, geological structure, blast design parameters, explosive properties, and environmental conditions were precisely scrutinized and evaluated.

This comprehensive approach allowed for the identification of critical variables and their relative impact on the PF. By extrapolating from these real-world scenarios, this study aimed to provide valuable insights and guidelines for optimizing blasting operations on steep rock formations, thereby enhancing safety and efficiency in such challenging environments.

2.2. General Constraints of Blasting Operations on Rock Slopes

Following an extensive geostructural survey, the development of a drill hole pattern necessitates a delicate balance among numerous constraints:

- Assessment of the rock quality and lithological and strength properties of the rock formations to ensure effective drilling and blasting outcomes;
- Understanding the joints' orientation (dip, dip direction) and characteristics of joints within the rock mass to optimize drilling angles and minimize potential instability;
- Implementation of measures to mitigate vibrations generated during drilling and blasting operations, reducing the risk of structural damage and instability of additional rock blocks or discomfort to nearby structures and communities;
- Determination of the required fragmentation size of the blasted rocks, in order to enable the required removal of the subsequent muck or material after blasting;
- Assessment of the accessibility of the drilling site to ensure efficient deployment of drilling equipment and personnel;
- Incorporation of time-sensitive requirements, such as the need to swiftly reopen roads or access routes, into the scheduling and execution of drilling and blasting operations.

By carefully addressing these constraints, the design of the drill hole pattern can be optimized to ensure safe, efficient, and effective drilling and blasting operations while meeting project objectives and minimizing potential impacts on the surrounding environment and infrastructure.

2.3. Risks and Undesired Effects

To address potential risks and unintended consequences in blasting activities, it is imperative to implement robust safety measures.

By implementing both preventive and protective measures, one can mitigate risks and unwanted effects associated with blasting activities, ensuring the safety of workers, surrounding communities, and nearby infrastructures while minimizing environmental impact; such measures include detailed inspection, localization of weak zones, and respect areas around the zone to be treated.

To achieve these goals, prioritizing prevention strategies, including risk assessments, is necessary.

A comprehensive training program for expert climbers, focusing on advanced safety protocols tailored for blasting operations on steep rock formations, must be included in the design requirements.

Stringent measures must be implemented to limit the occurrence of fly rocks, which pose a significant hazard to both workers and nearby communities.

Blasting operations should take care of residual surfaces to preserve the rock mass quality by adopting appropriate techniques such as presplitting, smooth blasting, etc. [13,14].

Mitigation with bolting and wire mesh or drapery systems, contouring the residual surface remaining after the demolition, can represent the final step of the blasting operations; therefore, local conditions can claim further access to expert rock climbers to remove fragments and to install bolts and drapery, starting from the top of the area.

2.4. Design Criteria

Even if, in the case of blasting an unstable rock element on a slope, the design criterion is most of the time more similar to ornamental stone cutting, the most straightforward parameter to check a blasting scheme remains the powder factor (PF).

It is important to conduct possible surveys with direct access to the slope with the help of climbers (specifically for joints conditions) and also by full recognition by means of unmanned vehicles (drones) to fully build a digital optical twin to describe distances and volumes; the use of drones is now complimentary for quick and complete volume descriptions and for supporting blasthole pattern configurations.

Geostructural, visual, and topographical surveys are also essential after blasting in order to verify the residual condition of joint surfaces and remove, by means of scaling techniques, unstable small blocks in order to finally proceed with the eventual protective/reinforcing works (typically drapery systems) and monitoring of major joints (crackmeters, topographic targets). Moreover, residual risk assessment after scaling and reinforcing remains of great concern for civil infrastructure, such as roads and tunnels [15] or for quarry yards.

The blasting criterion aims in this case to simply detach from the mountain the rock to be demolished, exploiting gravity. Compared to a situation where fragmentation is sought (e.g., a blasting operation for aggregates or industrial minerals), the operating philosophy is completely different: here, the effects sought are only those of detachment and, possibly, of rock displacement, which must detach from the original rock mass, falling downstream with the help of gravity; this operation is correctly referred to as cutting and not as demolition.

As proof of this, the specific consumption found in these cases is much lower than normal for industrial materials. The cut is normally obtained by a series of side-by-side holes, often of small diameter (normally ranging from 48 mm to 51 mm). The blasting design essentially consists of determining the distance between the holes and the charge per hole.

A very simple design method based on a quasi-static approach to the explosion phenomenon is now described. It is assumed that the force generated by the pressure of the explosion gases in the holes must overcome the tensile strength of the rock between two adjacent holes, as exemplified in Figure 1.

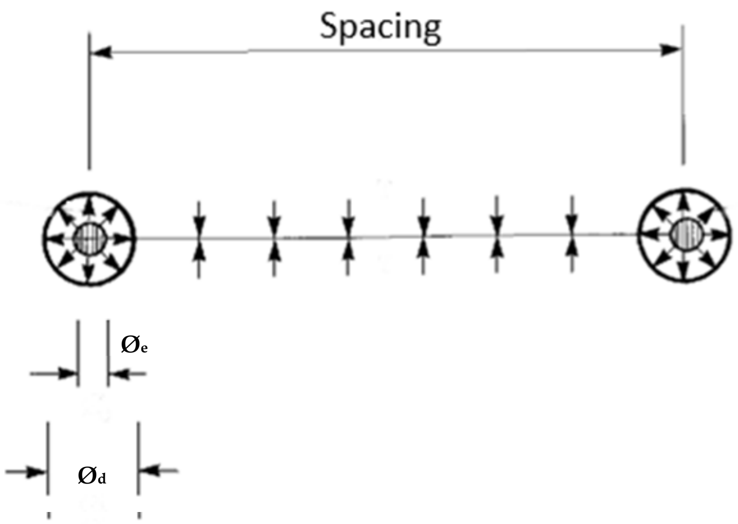

Figure 1. Scheme of mechanism of explosive cut-action according to quasi-static approach for new fracture formation between adjacent blastholes—modified from [16].

The pressure Ph inside the hole is a function of the specific pressure of the explosive (Pe). The input parameters are as follows:

- Type of explosive.
- Drilling ($Ø_d$) and explosive ($Ø_e$) diameter (i.e., cartridge diameter).
- Length of hole (L_h).
- Explosive length (L_e).
- Tensile strength of rock (T).

By imposing the static equilibrium of the system, the following formula for calculating the Spacing (S) between the holes in the same row can be obtained [16]:

$$S = Ø_d + \frac{Ø_d}{kT} P_h \rho_e \left(\frac{L_e}{L_h}\right) \left(\frac{Ø_e}{Ø_d}\right)^2 \tag{3}$$

where

- ρ_e is explosive volumetric mass;
- k is a coefficient that takes into account the effect of the alignment of the holes, which ranges from 0.5 (if the spacing between the holes is less than 10 * $Ø_d$) to 1 when the spacing is higher (more than 30–40 * $Ø_d$).

The tensile strength of rocks is not always easy to obtain, especially when considering factors like schistosity. Schistose rocks indeed pose challenges due to their varying strengths in different directions. In the first hypothesis, we can refer to the uniaxial compressive strength, assuming that the tensile strength is on average 1/20 of the uniaxial compressive strength. However, this value is not very reliable: this underscores the importance of comprehensive testing and understanding of the specific properties of the rock in question. Specific phenomena affect the behavior involving tensile strength: for example, it was found that the stress–strain relation is quasi-linear up to failure, which occurs in a brittle way. The stiffness modulus values and apparent tensile strength depend on the inclination of the schistosity concerning the loading direction [17]. For rock materials, the compressive strength is generally about 8–15 times higher than tensile strength, apart from some exceptions (serpentinite rocks, for example). The scattering is always relevant, even for the same rock type. Moreover, in site conditions, weathering acts on the rock matrix and along joints and microcracks. In order to avoid a final excess in the blasting charge, and in thus rock fragment projections (flying rocks), it is preferable to reduce the ratio and to keep the blastholes spacing (well defined) as it is. It should be suggested, as a rigorous approach, to test a specimen from the site in a lab or by means of a point load testing apparatus in order to properly adjust the blasting scheme parameters. In the authors' experience, obtaining permissions for preliminary blasting trials on-site remains quite hard.

2.5. Analysis of Case Histories for Validation

A summary of the specific case histories analyzed in the research is proposed below. Some of them have been designed, applied, and controlled directly by the authors.

1. The first one was presented in [18] and concerns the blasting of a large dangerous block (about 60,000 m^3) overhanging the village of Meiringen, Switzerland (Figure 2). The initial intervention stemmed from the looming threat of a significant rockfall poised to engulf the town. Minor detachments from the limestone cliff, situated approximately 340 m above the town, had already been documented. The rock mass was Dogger limestone, exhibiting relatively robust resistance properties with a tensile strength of 5 MPa and a shear strength of 11 MPa. To ensure optimal safety measures, the blasting parameters were meticulously calibrated, employing a dense drill hole pattern to facilitate the fine fragmentation of the material. This is, on the other hand, an ever-present concern in this kind of blasting, as the uncontrolled fall down of large intact blocks can lead to substantial damage to infrastructure and does not allow forecasts of falling trajectories. Hence, the aim was to limit the size of blasted blocks to no more than 1 cubic meter. To protect the town, the construction of a sturdy stone embankment was performed along the forecast fall down path, capable of containing an estimated volume of around 60,000 m^3. The blasting was carried out in four distinct rounds.

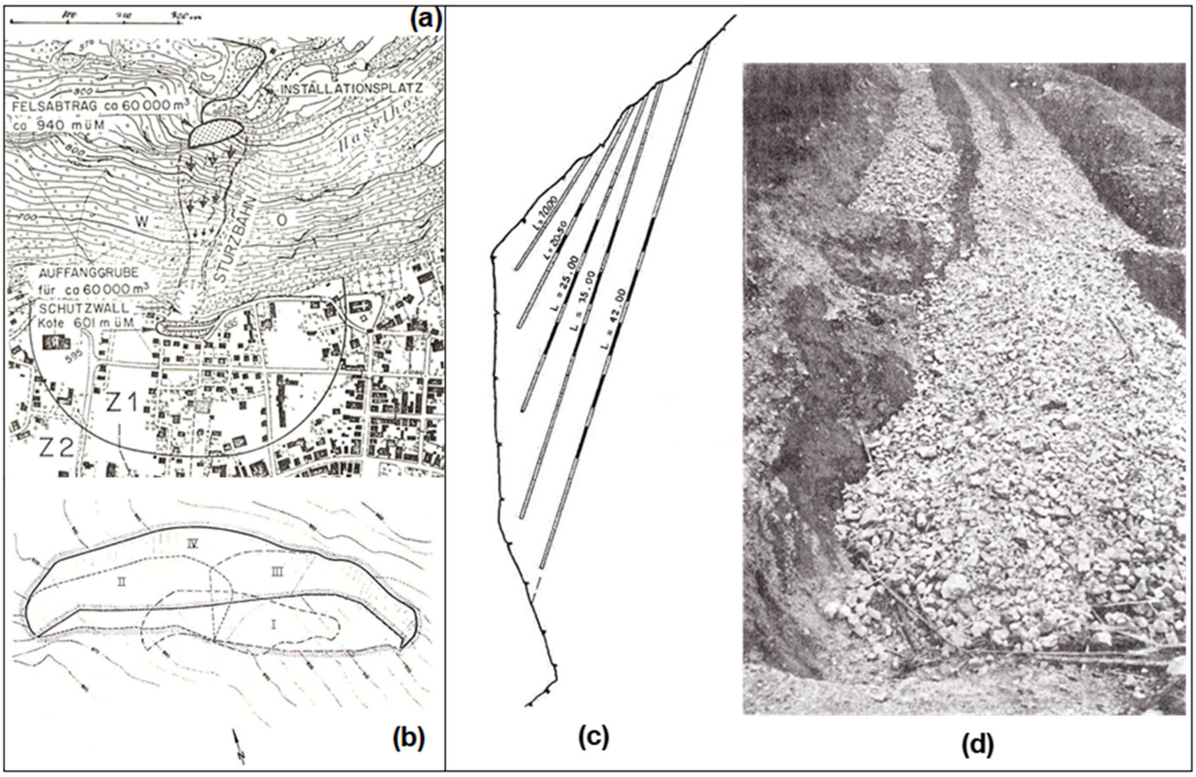

Figure 2. The case of Meiringen in Switzerland. (**a**) Plan view of the blasting project. Z1 area to be evacuated; (**b**) detailed plan with the subdivision of the block to be blasted in 4 rounds; (**c**) lateral section of the drill hole pattern from the firing plan of the second round; (**d**) view of the muck fan after the first round (modified after [18]).

2. A second case on Quebec highway 155 (Figure 3) is described in [19], motivated by the danger represented by a potentially unstable rocky dihedral of a volume of about 800 m^3 looming over the road, passing at an altitude of 30 m lower. The rock was andesitic gneiss of the Precambrian age. The analysis of stability indicated a very low safety factor, which was variable from 1.16 to 1.06 depending on the assumed friction angle.
   The PF adopted, decidedly enormous for European standards, was about 0.77 kg/m^3, probably motivated by the need to achieve very fine fragmentation. Blasting has been implemented with micro-retarded electrical detonators. Before the blasting, the road below was protected with a sand bed 1 m thick.

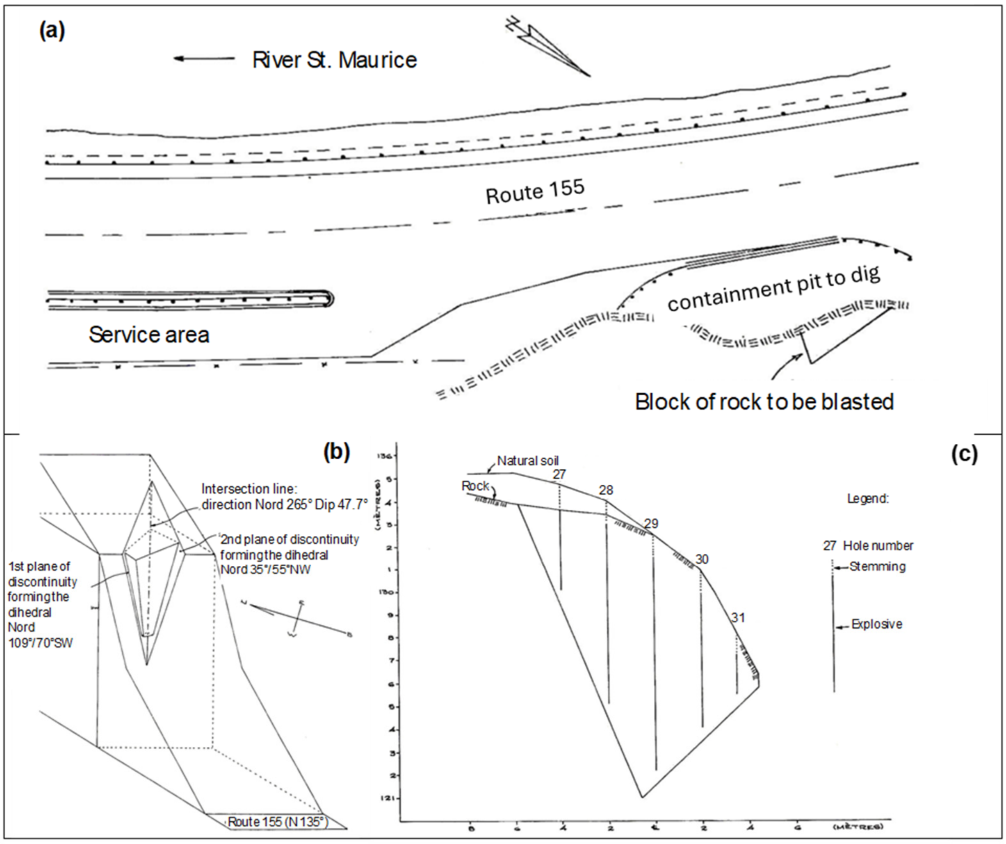

Figure 3. The case of Quebec highway 155. (**a**) Plan view of the blasting project; (**b**) perspective view of the dihedral to be blasted; (**c**) lateral section of the drill hole pattern from the firing plan (modified after [19]).

3. A further example related to the blasting of an overhanging block is shown in Figure 4 [20]: a local mountainside road in the northwest of Italy (the provincial road of Val Mastallone in Cravagliana, Vercelli province), which was periodically closed due to minor rockfalls after rainfall events and thawing periods.
   The object of the blasting is a spur in unstable conditions with a volume of about 2500 m^3, as made clear by a previous collapse. The slope is made of weathered gabbric rock with a uniaxial compressive strength of 90 MPa and tensile strength of 8.5 MPa. This stretch of road was subjected to a systematic collapse of rock blocks of various sizes. Particularly critical was the earlier collapse of 1000 m^3, from just below the blasted rock induced by a planar slide. The blasting design, provided by the authors, requested a preliminary careful geostructural survey to clearly define the persistence and location of main joints at the rear of the potential unstable volume. Both drilling and charging have been prepared by using both a hydraulic long-arm

platform and the experience of skilled climbers along the slope. Non-electric ignition has been adopted.

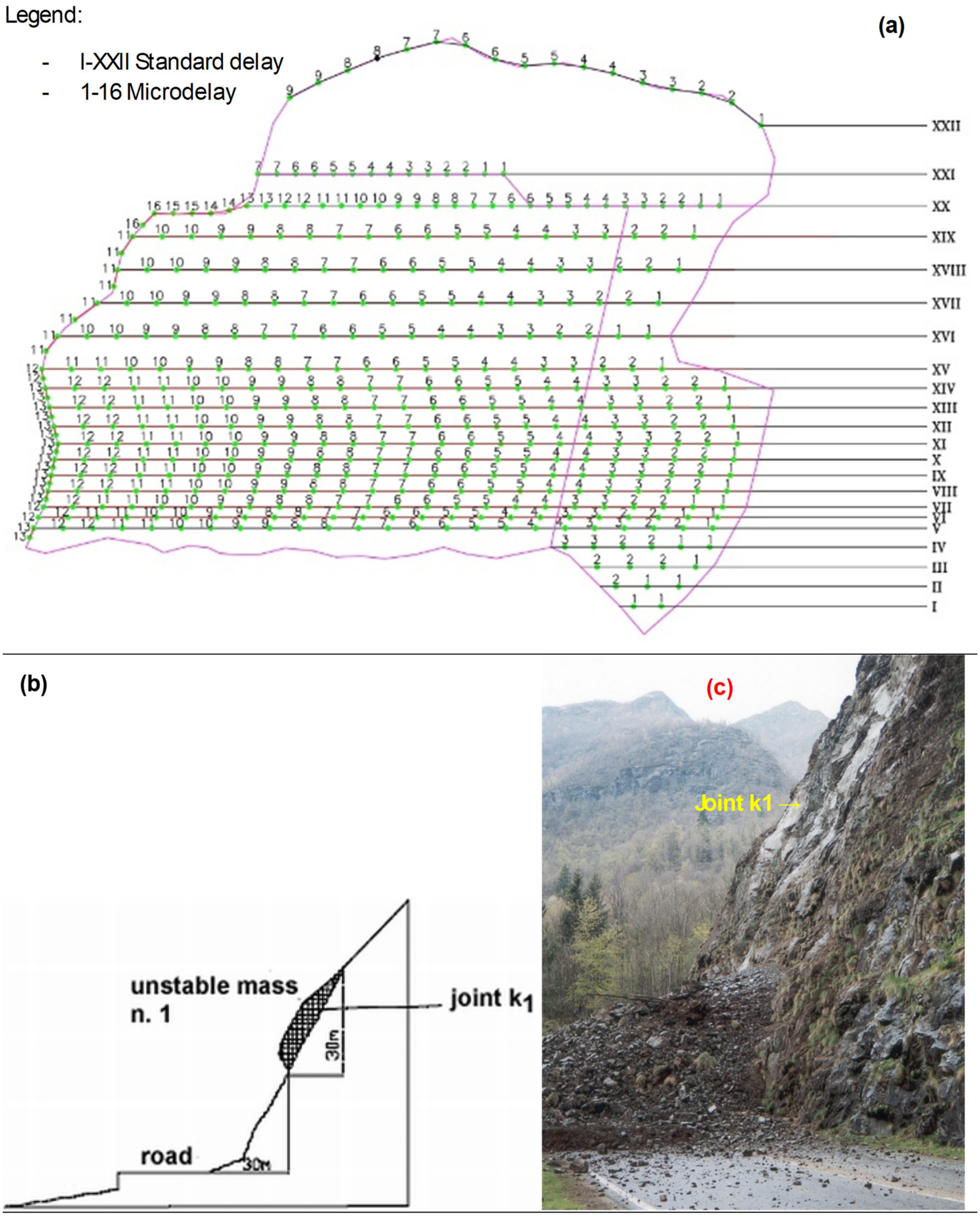

Figure 4. The case of the provincial road of Val Mastallone in the northwest of the Alpine range in Italy. (**a**) Firing plan (non-electric ignition has been adopted); (**b**) schematic cross section; (**c**) result of the blasting, with rock fragments accumulated in a regular shape on the road at the base of the slope (paving was protected from impacts with a granular debris cover) (modified after [20]).

4. The case of the demolition of an unstable monolithic slab (Figure 5) [20] of porphyry rock about 10 m wide, 33 m high, and 2–6 m thick, with a global size of about 1300 m^3, that threatened a road with a high traffic density of more than 1 car/min: the

provincial road Gattinara-Borgosesia in Serravalle Sesia (Vercelli province—Italy). The monolith was totally isolated from the rock mass of the slope by two open joints and its base was an irregularly and highly fractured rock portion. The authors carried out a local geostructural survey to help with the design of the blast round. The probability of occurrence of a sudden collapse of the slab was very high.

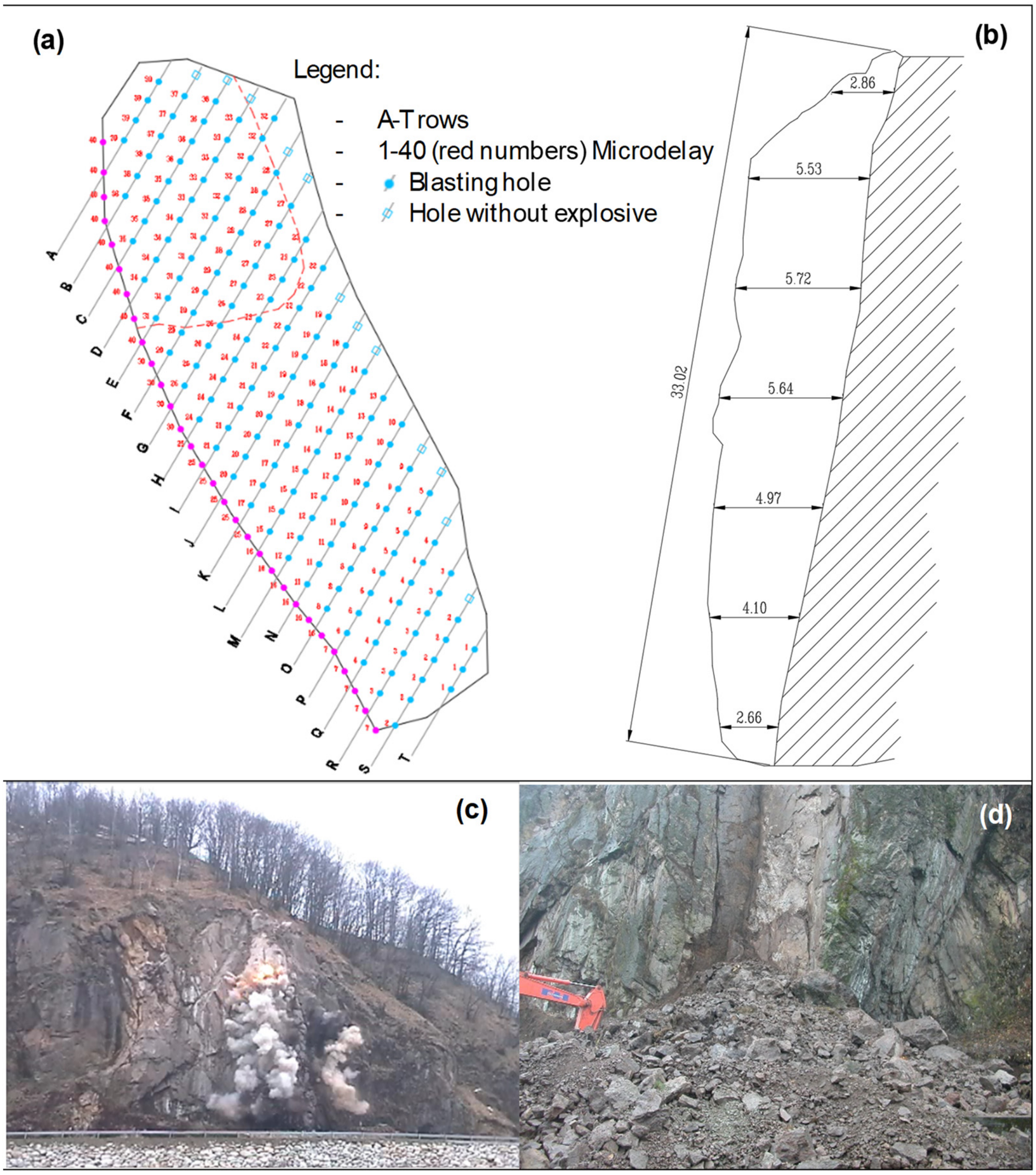

Figure 5. The case of the provincial road Gattinara-Borgosesia in the northwest of the Alpine range in Italy. (**a**) Firing plan designed by the authors; (**b**) cross section with measures in m; (**c**) the ignition of the round (non-electric ignition has been adopted); (**d**) result of the blasting in terms of fragments size on the road (paving was protected from impacts with a granular debris cover) at the base of the subvertical slab (modified after [20]).

Other relevant original cases, presented here for the first time, are the following:

5. The demolition of a set of mutually bound blocks above provincial road 169 of Val Germanasca (Turin province) in Northern Italy (Figure 6). The rock was in this case a minute gneiss of mediocre quality and the total volume of the blocks was about 640 m^3. In this case, which was known for decades for the inherent hazard it posed to

road traffic, the greatest risk during the blasting was represented by the possibility of shearing the explosion line, following the beginning of the round, for the induced movement of the individual blocks. This phase did not stand alone, but after an arranged detailed local geostructural survey, a blasting design was carried out by the authors; after blasting, manual scaling and a strong and wide reinforcing of the rock slope was carried out (bolting, draperies, cable securing, net fences to intercept fragments fall along the slope). Before and after demolition, scaling operated by climbers was carried out to achieve better safety for work along the slope.

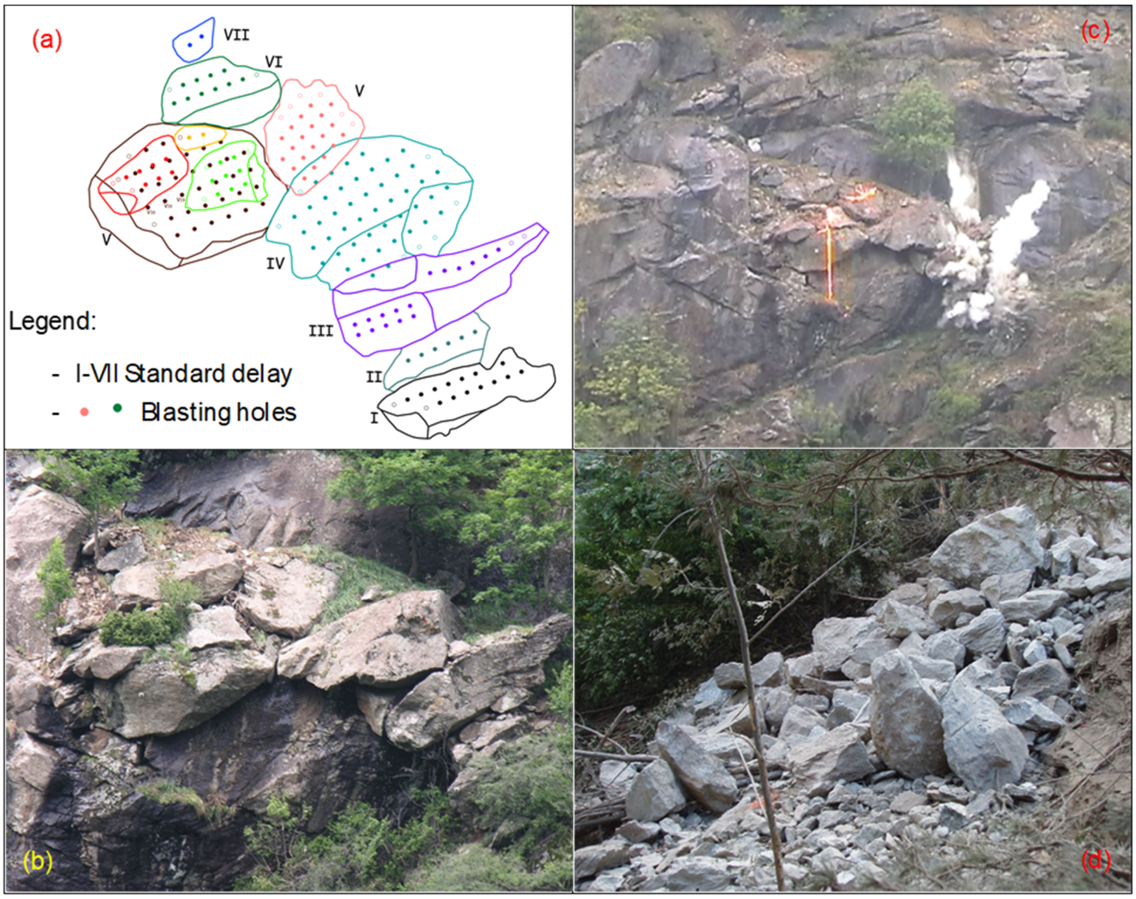

Figure 6. The case of provincial road 169 in Val Germanasca in the northwest of the Alpine range in Italy. (**a**) Firing plan; (**b**) overall view of the block set; (**c**) the ignition phase of round; (**d**) result of the blasting resulting in large blocks. Consider that the difference in elevation of the claimed volume and the base road was about 130 m.

6. This case considers the demolition of a highly unstable monolithic block (Figure 7) of about 6000 m^3 within a quarry area in Northern Italy, overlooking the quarry square. The rock was represented, in this case, by a gneiss of excellent quality (orthogneiss), with a compressive strength of 185 MPa, mainly used for ornamental purposes. The firing plan was studied by the authors to obtain a fragmentation between 0.5 and 2.0 m^3 in order to allow the subsequent reuse of the blasted rock as by-products.
   Obviously, the main purpose of the blasting demolition was to improve the safety conditions of the site; however, when it is possible to recover and recycle blasted rocks, it is a good practice to do so in order to obtain new products/by-products for civil, building, road, and environmental applications.
   In a similar vein, when a rock slide occurs along a mountainside where road or infrastructures are present, it becomes urgent and necessary to remove the collapsed

material, and its possible reuse (as aggregate, for backfilling, for embankments) depends also on the blocks' fragment size distribution, especially to fulfill technical requirements concerning compaction and consistency.

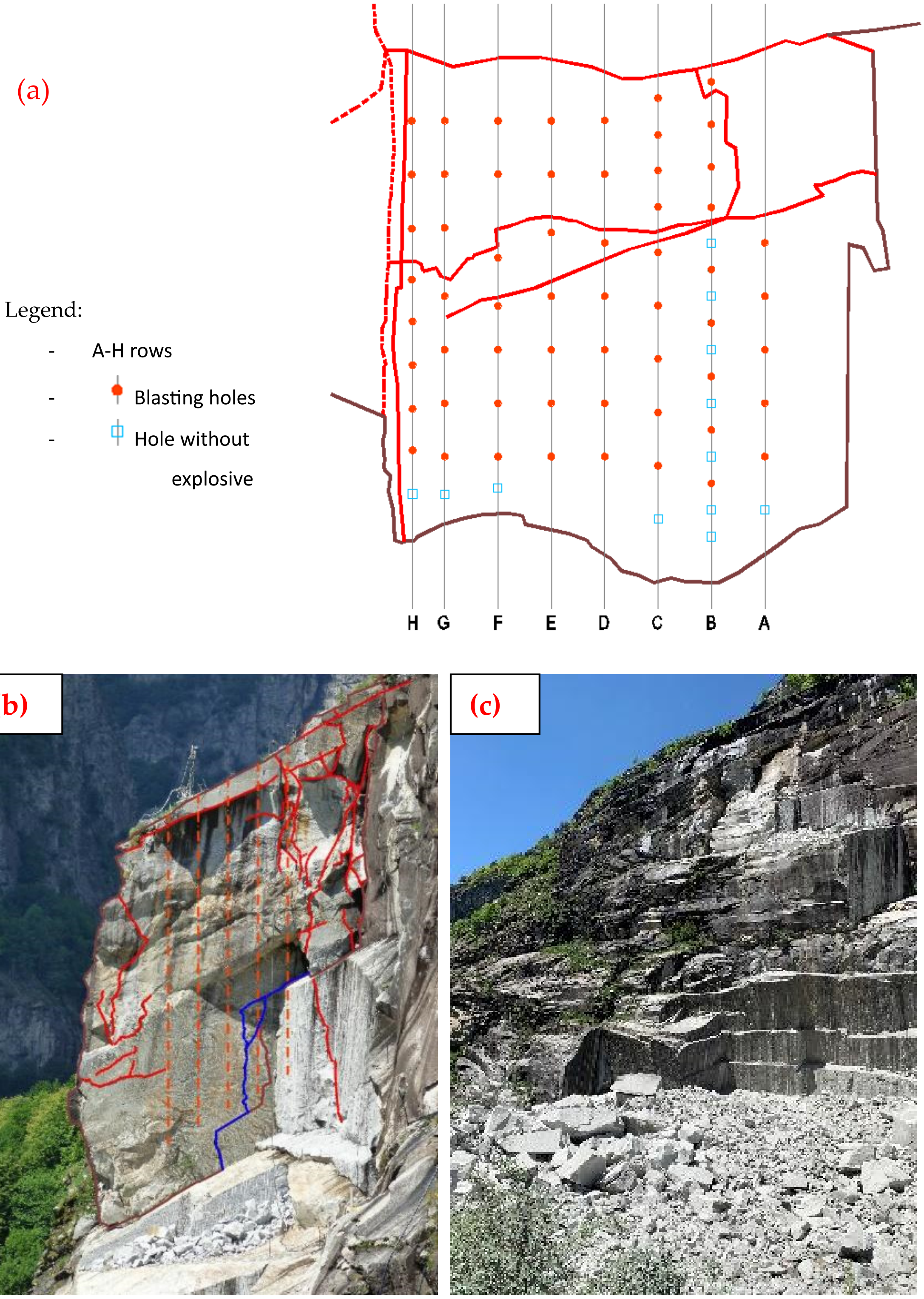

Figure 7. The gneiss quarry in Northern Italy. (**a**) Firing plan (top view) with the locations of blastholes drilled vertically, as designed by the authors. (**b**) Cross section with drilled holes; in red, joints and fractures, in orange blastholes, in blue rear fracture; the bench is about 25 m high. (**c**) Result of the blasting: in the upper part of the quarry face, the 'clean' and regular residual surfaces are visible, as is the blasted material in the quarry yard at the base.

In the following, Table 1, a summary of the main parameters for each considered case for our analysis is given.

Table 1. Overview of the main parameters.

Case Studies	Rock Type	Total Volume (m^3)	Fragmentation	Prevalent Explosive Type	Drilling Diameter (mm)	Spacing in Row (m)
Meiringen (Switzerland)	Limestone	60,000	high	ANFO	85	3.0
Québec motorway (Canada)	Precambrian andesitic gneiss	800	very high	ANFO	63	1.5
Cravagliana (VC), Italy	Weathered gabbro rock	2500	very high	slurry	41	1.25
Le Cave (VC), Italy—Slab	Porphyry rock	1300	high	slurry	41	1.1
Perrero (TO), Italy—Catasta	Minute gneiss	640	normal	dynamite	34	1.0
Balmoreglio quarry (VB), Italy	Serizzo (gneiss)	6000	normal	watergel	51	2.0

3. Results

Starting from the antecedents cited in Section 2.4, the formula presented here for determining and dimensioning the blasting of an unstable rock element on a rock slope assumes the following expression:

$$PF = K * (S/Ø_d) * R * E * (F * D) \tag{4}$$

where

- K is a numerical coefficient depending on the rock behavior at failure;
- S is the spacing between two holes of the same row;
- $Ø_d$ is the drilling hole diameter;
- R is a coefficient referring to rock type;
- E is a coefficient referring to explosive features;
- F is the desired fragmentation effect;
- D is the desired displacement of the blasted material.

It can be observed that $(S/Ø_d)$ represents the ratio of the rock's resistance surface to the surface (represented by the diameter of the hole) on which the pressure of the explosion gases is applied.

K is taken as 0.0059. According to [11], the rock coefficient R takes the values shown in Table 2.

Table 2. Division into classes for rock types.

Class	Rock Type	R
1	quartzites and compact porphyries	1.30
2	sound granitoid rocks, gneisses, basalts, gabbro rock	1.00
3	compact limestone and dolomite, grés, highly cemented sandstone	0.90
4	phyllites, hard shale clay, serpentine	0.80
5	marl and soft limestone, gypsum, poorly cemented sandstone	0.50

Table 3, related to explosives, applies the same reference but reproduces the types of explosives currently used.

Table 3. Division into classes for explosive types.

Class	Explosive Type	E
1	nitroglycerine, dynamite	0.95
2	slurries, watergel	1.00
3	ammonium nitrate (ANFO)	1.10

To increase the degree of fragmentation of the blasted rock, as well as to move the heap of the blasted material, additional energy is needed, which is provided with an increase in the employed explosive. The coefficients F and D in Tables 4 and 5 increase the estimated value of PF according to these concepts.

Table 4. Increase in FP to achieve greater fragmentation.

Class	Fragmentation	F
1	normal (several blocks bigger than 1 m^3)	1.00
2	high (maximum size up to 1 m^3)	1.20
3	very high (maximum size up to 0.5 m^3)	1.40

Table 5. Increase in FP to obtain displacement of blasted rock.

Class	Displacement	D
1	no additional displacement in addition to the action of gravity	1.00
2	additional displacement required (few meters)	1.20
3	high additional displacement required (10 m or more)	1.60

By applying Equation (4) to the real cases described in Section 2.4, the following results are obtained:

4. Discussion

Generally, a good match between the real (PFr) and calculated (PFe) powder factors can be observed. The only exception is case study n. 2 from Quebéc. The PFr used in this case is much higher than in other cases and has already been reported as anomalous [21]. In order to make the various PF values comparable, they are normalized to the empirical coefficients R, E, F, and D.

Figure 8 shows the normalized values of the real powder factor PFr and the calculated power factor PFe as a function of the ratio between the spacing of the drilled holes along the same row and the selected borehole diameter. The trend of the normalized PF values is represented by the line of equation PF = 0.0059 * (spacing/drilling diameter) + 0.0009. The PF obviously increases with the increase in the ratio between the spacing and diameter of the hole. The latter varies in the range 24–40, which is in good agreement with field experiments in the literature [22,23]. It should be outlined that demolition for securing a slope can follow different partial goals: cases n.3 and n.4 were finalized with a driven fragmentation in order to protect the road pavement, while in case n.5, the aim was the removal of huge unstable and distressed rock elements, with little concern for the size of fragments—something that should have be flagged regarding hazards during drilling by the rock climbers.

Comparing the proposed solution for the blasting of impervious and critical portions of rock slopes with current blasting schemes or other solutions (reinforcing or protection), it appears that this study can help improve the efficiency of results, optimize the consumption of explosives, reduce excess vibration and fly rocks, and enable such operations to occur in safer working conditions: more care put into investigating the rock mass structure and blasting scheme turns into improved final results. For example, in terms of local geostructural characterization, seismic surveys, specifically where the installation of a geophone array becomes possible, should help to detect possible hidden persistent joints at the rear, even if P-wave velocity detection alone does not appear sufficient to evaluate and classify rock masses, because characteristic impedance may be taken as a comprehensive index to evaluate and classify rock masses [24], as it is evident that the properties of rock formations constitute a decisive factor in determining the parameters of drilling and blasting operations [25]. Valuable data from the multichannel analysis of surface waves (MASWs) could be used for the selection of explosives with the desired velocity of detonation and density, so as to match the impedance of rock mass [26]; these data could also be used with the development of algorithms to match the relevant impedance for selecting the right type of explosive [27].

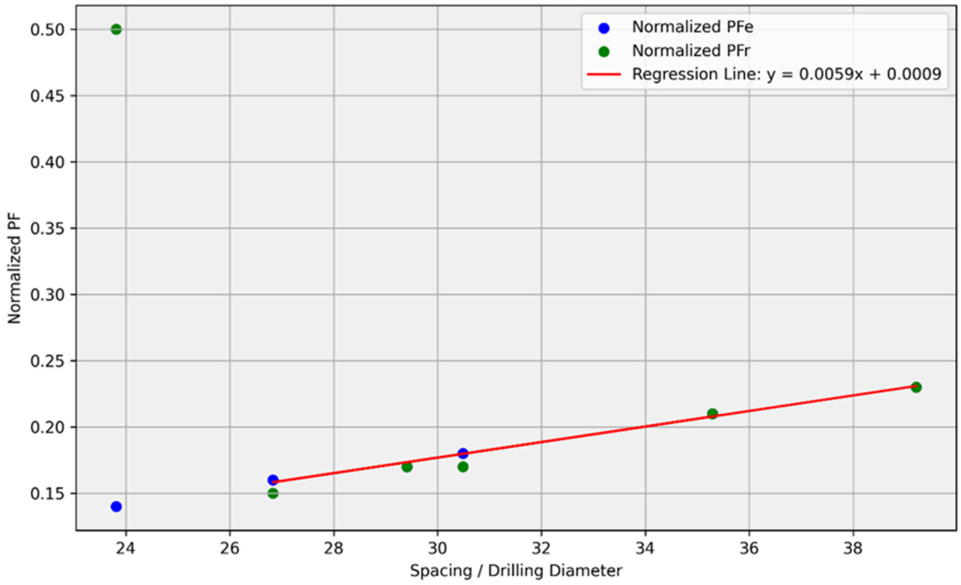

Figure 8. Normalized powder factor (PF) vs. ratio spacing/borehole drilling diameter.

Using explosives to remove unstable rock elements on rocky slopes presents a viable and often efficient solution for enhancing safety conditions. This method offers advantages in terms of speed, cost-effectiveness, and minimal subsequent maintenance interventions compared to alternative techniques.

The proposed innovative PF formula provides a simple and robust tool for optimizing blasting designs, allowing engineers to tailor interventions based on site-specific conditions and operational goals. By integrating real-world validations, the method offers actionable guidelines that can streamline blasting designs while ensuring safety and cost-effectiveness.

Through an in-depth analysis of various case studies, this study aimed to establish control parameters, particularly the powder factor (PF), for optimizing blasting schemes on rocky slopes. The PF serves as a synthetic parameter indicative of blasting efficiency, influenced by factors such as rock type, explosive properties, blast design, and desired fragmentation, eventually taking into account the stress or load level, as rock breakage by blasting is directly proportional to the exposed rock's stress level and pre-blasting conditions [28]; on this topic, comparison with other approaches could be applied for cross-validation, namely, after fragmentation determination by image analysis and after constraints are selected, when they are used in optimization control of the performance [29].

While traditional blasting formulas exist for tunnel and open-air bench blasting, specific criteria for blasting single elements on slopes are lacking. The proposed formula for PF calculation incorporates parameters such as hole spacing, rock and explosive characteristics, desired fragmentation, and material displacement. Real-world case analyses revealed a correlation between calculated and real PF values, with exceptions attributed to anomalous conditions. Normalized PF values showed an increasing trend with the ratio of spacing to drilling diameter.

Despite the effectiveness of explosives in slope stabilization, challenges persist, including the variability of rock properties and the need for precise blasting designs to prevent adverse effects such as fly rocks and overbreaking at the rear residual surfaces. Safety measures, such as risk assessments, comprehensive staff training, and protection of in place surfaces, are essential to mitigate risks associated with blasting operations at civil and mining sites, also combined with protective countermeasures [30,31].

The considered experiments and engineering judgments made on available data can allow one to observe that even if explosives offer a valuable tool for improving safety conditions on rocky slopes, their use requires meticulous planning, adherence to safety protocols, and consideration of site-specific factors to ensure optimal outcomes while minimizing risks and environmental impacts; additional features such as the distribution of rock fragments can be considered for comprehensive results [32,33].

5. Conclusions

This study's concluding remarks are based on its meaningful field experiments, which demonstrated that while explosives offer a valuable tool for improving safety conditions on rock slopes, their use requires meticulous planning, adherence to safety protocols, and consideration of site-specific factors to ensure optimal outcomes while minimizing risks and environmental impacts.

In particular, the following issues can be pointed out:

(a) The relationship between row spacing, spacing, and detonation sequence is embedded within the PF formula, where these parameters influence fragmentation and displacement outcomes. Empirical correlations derived from case studies (Table 6) highlight how adjustments in spacing and sequencing can optimize energy distribution, reducing overbreak and enhancing safety. Future research will aim to quantify these interdependencies further, potentially integrating numerical simulations for greater predictive accuracy.

(b) Developments and data collection should prioritize the investigation of additional real-world cases to bolster the robustness of the proposed formula for calculating the powder factor. Researchers can refine and validate the formula by analyzing a wider range of scenarios, ensuring its applicability across diverse geological and operational contexts. This expanded dataset will provide a more comprehensive understanding of the factors influencing blasting efficiency and allow for the identification of any additional variables that may impact the accuracy of the formula. Additionally, incorporating data from a variety of case studies will enhance the reliability and generalizability of the findings, ultimately contributing to more effective and precise blasting practices along rock slopes.

(c) The prospects for possible applications in excavation works or in geomechanical cases are related to the refinement of blasting scheme parameters according to a more reliable approach balancing and prioritizing the various involved factors: lab or site rapid testing, care regarding spacing and aperture estimation for joint structures, and the assessment of physical connections between rock volumes (rock bridges) for determining a progressive and complete kinematic evolution. Also, remote surface acquisition (photogrammetry or laser scanning) helps to build up the geometrical model and direct inspection with climbers and with unmanned vehicles (drones) is fundamental to detect possible persistent and hidden joints at the rear of slopes. Civil work (excavation or reclamation of impervious slopes), mining and quarrying bench profiling, and reinforcing work in mountain areas represent possible fields of application.

Table 6. Comparison between real FP and those obtained by applying Formula (4) to case studies.

Case Study	K Coefficient	Rock Coefficient "R"	Explosive Coefficient "E"	Fragmentation Coefficient "F"	Additional Displacement Coefficient "D"	PF Real (kg/m^3) PFr	Estimated PF (kg/m^3) PFe
Meiringen (Switzerland)	0.0059	0.50	1.10	1.20	1.20	0.30	0.30
Québec motorway (Canada)	0.0059	1.00	1.10	1.40	1.00	0.77	0.22
Cravagliana (VC), Italy	0.0059	1.00	1.00	1.40	1.00	0.24	0.25
Le Cave (VC), Italy—Slab	0.0059	1.30	1.00	1.20	1.00	0.24	0.25
Perrero (TO), Italy—Catasta	0.0059	1.00	0.95	1.00	1.00	0.16	0.16
Balmoreglio quarry (VB), Italy	0.0059	1.00	1.00	1.00	1.00	0.23	0.23

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