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Numerical Modelling and Intervention Measures for Snow Avalanche Protection of the Blattbach Railway Tunnel

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Abstract **-** Snow avalanches represent an undeniable reality in the Swiss Alps both as a geomorphic process and as a type of hazard, causing fatalities, damage to structures and infrastructures. The potential damage of snow avalanches must be seriously taken into consideration when new infrastructure is planned in snow-avalanche prone areas, or to protect existing ones. The Matterhorn Gotthard Bahn railway line is a Swiss infrastructure periodically subjected to snow avalanche hazard in some critical area. This research, in the frame of the practical applications that SUPSI (University of applied sciences of southern Switzerland) promotes within the civil engineering bachelor's degree program, provides a preliminary study aimed at investigating the best protection measure for avalanche risk mitigation of the infrastructure. Snow avalanche simulation are performed and calibrated based on available data obtained from historical events, allowing to estimate the avalanche debris height, length, and speed. On these basis, three solutions are proposed to handle avalanche situations, respectively an increase of the existing tunnel length before and after the critical area, some deviation earth-compacted embankments, or avalanche protection steel barriers. Different solutions are analysed and compared in terms of efficiency and costs.

***Keywords*:** snow avalanche; natural hazard; numerical analysis; intervention measures; protection tunnel; embankment.

1. Introduction

Snow avalanches are defined as gravity-driven flows in earth surface systems with a volume greater than 100 m^3 along a slope for a distance of at least 50 m and represent one of the most frequent natural hazards in the alpine areas ([1]). As debris flow or mudflow, they constitute a threat for human lives, ecosystems, landscapes, and infrastructure in mountainous regions ([2]-[3]-[4]-[5]-[6]). With an annual average of 138 fatalities due to snow avalanches, estimated by the International Commission for Alpine Rescue based on 20-year survey in North America and Alpine countries, the risk of snow avalanches is increasing worldwide due to climate change ([7]). According to [8], the climate warming is identified as one of the factors influencing the increasing hazard frequencies of snow avalanches. Natural activities (earthquakes, heavy snowfall, and warm air temperature), and human activities (military activities, traffic construction, prospecting, mining, mountaineering) are commonly recognised as triggers of snow avalanches ([9]). All of these can result in human casualties and infrastructure losses, therefore, when new infrastructure is planned in snow-avalanche prone areas, the potential damage of snow avalanches must be taken into account ([10]-[11]). The current study is aimed at preliminary investigating the best protection measure for avalanche risk mitigation of a Swiss railway line subjected to snow avalanche hazard. Numerical snow avalanche modelling is performed and calibrated to propose mitigation measures that are compared to investigate the better solution in terms of both efficiency and costs.

2. Case study

The Matterhorn Gotthard Bahn (MGBahn) is a Swiss railway line located between Stalden and Täsch municipalities. This infrastructure crosses twenty potential snow avalanche paths that could arise problems for train traffic in the case of interruption of the line. The current study deals with the most snow-avalanche prone area lying within the Blattbach area at an average altitude of 1’200 m above the seal level, covering a surface approx. 171’000 m^2. In this area a 131 m long tunnel was already built in the early ‘900 to protect part of the railway line both from debris flow and snow avalanches (Fig. 1).

Fig. 1: Geographical location of the area of interest ([12], scale: 1:500’000) and overview of the Blattbach railway line. The dotted line represents the 131 m existing tunnel ([13]).

In the last decades, many snow avalanches occurred in this area, so that Blattbach area is considered the most critical zone. Four major historical snow avalanches occurred on the Blattbach area, causing the covering of the railway tracks both to the South and to the North of the tunnel portals, respectively in 1945-1988-1999 and 2018 (Fig. 2 and Fig. 3).

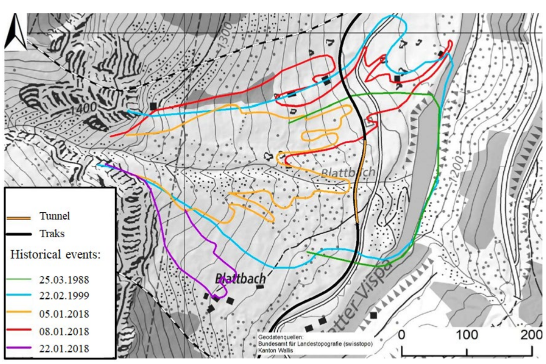


Fig. 2: Invaded areas by the four major snow avalanches ([12]).

Fig. 3: Historical snow avalanche occurred in 2018. The orange line represents the existing Blattbach tunnel ([14]).

This preliminary research, in the frame of the practical applications that SUPSI (University of applied sciences of southern Switzerland) promotes within the civil engineering bachelor’s degree program, is aimed at studying the snow avalanche phenomena, allowing to investigate possible intervention measures to avoid the track burial every 10 to 15 years.

3. Numerical modelling of the snow avalanche

The snow avalanche simulations have been performed by using RAMMS: AVALANCHE software ([15]). Based on on the Distinct Element Method (DEM), the code allows to predict the avalanche runout distances, flow velocities and impact pressures in three-dimensional digital terrain model (DTM). An estimation of the snow avalanches motion from from initiation to runout can be performed, allowing to solve both smaller mass movements as well as larger, extreme avalanche events. All numerical simulations in the current research have been performed by considering a snow avalanche avalanche 30-years return period, corresponding to the historical events occurred respectively in 1988, 1999 and 2018. The snow avalanche has been modelled according to Voellmy Salm rheology model, a non-linear model that simulates the mixture motion as a homogeneous mass flow ([16]). Commonly used for analysing the frictional terms of non-Newtonian flows, the model explains the motion of snow avalanches, pyroclastic flow, and granular debris flow based on the following constitutive equation:

$$\tau = \mu\rho g h + \rho g U \frac{v^2}{h\xi} \tag{1}$$

where the first term is the Coulomb friction stress (τ_μ), which linearly depends on the flow depth (h) and dry Coulomb friction (μ). The second term explains the turbulent friction stress (τ_ξ) which directly depends on the square of the velocity (v) and inversely proportional to the turbulent frictional coefficient (ξ). The ranges of these coefficients largely depend upon the type of sediment involved in the flow: for snow avalanches, the Coulomb friction ranges from 0.1 to 0.6, while the turbulent frictional coefficient ranges between 50 ms^{-2} and 4000 ms^{-2}. Then, the area of interest (Fig. 4), allowed to localize 27 potential release area having a ground slope between 30° and 50° (Fig. 5).

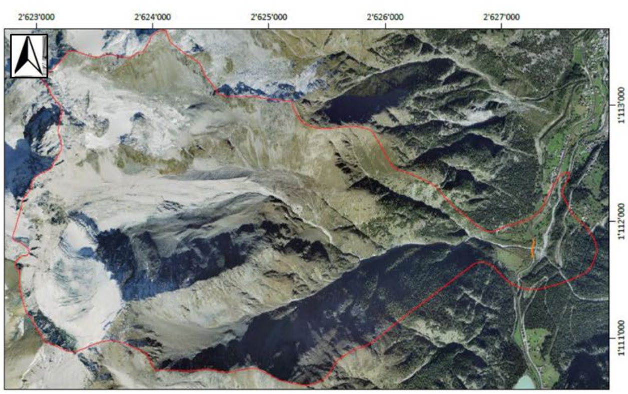


Fig. 4: Area of interest ([12], year 2020).

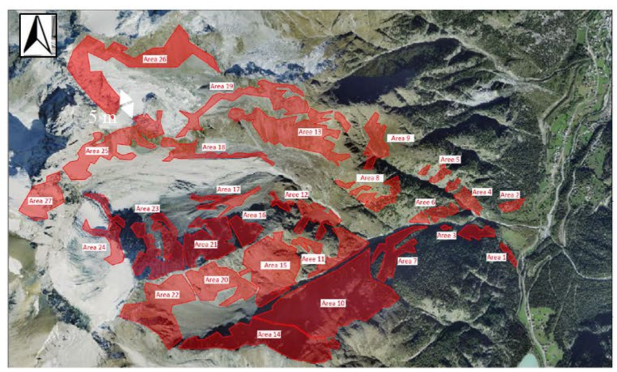


Fig. 5: Potential release area ([12], year 2020).

According to the Swiss Regulations ([17]), the release height H_d of a potential snow avalanche is the thickness measured perpendicularly to the slope of the unstable snow mass:

$$H_d(T;z) = \left[\Delta H3_{gg}(T;z) + H_{sd}\right] \cdot \cos(28°) \cdot f(\theta) \tag{2}$$

where $\Delta H3_{gg}(T;z)$ is the increase in snowpack height after three consecutive days of snow precipitation depending on the considered area, return period (T) and average altitude (z), H_{sd} is the snow height carried by the wind, and f(θ) is a decreasing function of the average slope (θ) of the release area. The latter is evaluated as follows:

$$f(\theta) = \frac{0.291}{\sin(\theta) - 0.202 \cdot \cos(\theta)'} \quad \text{with } \theta > 28° \tag{3}$$

For each release area ($A_1 \rightarrow A_{27}$), the above parameters have been evaluated according to the procedure detailed in [14] and numerical simulation run. The release area A_{10} was proved to give the most realistic simulation (S_{10}) if compared with the historical snow avalanche occurred in 1999 in terms of snow-covered surface. The release area A_{10} considered in simulation S_{10} is represented in Fig. 6, while the input parameters are provided in Tab. 1. A comparison of the avalanche runout distances experienced by snow avalanche in 1999 and the three-dimensional simulations (accuracy: ±3 m) is provided in Fig. 7: accordance between the historical event and the numerical results in terms of covered area can be observed. The covered area during the event occurred in 1999 and predicted area are almost the same at North side of the existing tunnel, while some difference at the South side (about 50 m) could be observed, and it is supposed to be due to the presence of dense vegetation along the southern slope alongside the snow avalanche path, which is not completely taken into account in the simulation.

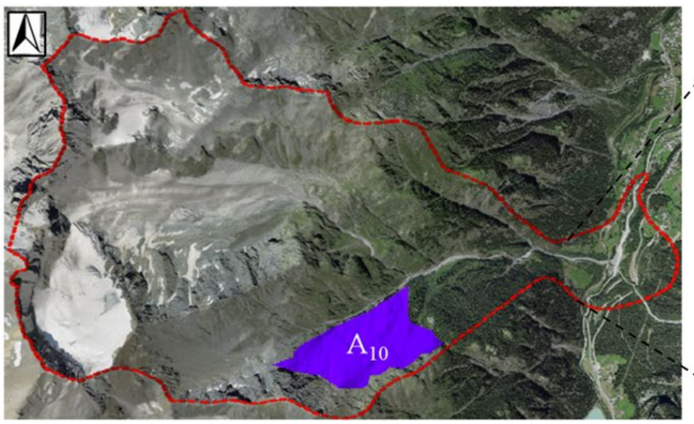


Fig. 6: Release area A_{10} considered for the numerical simulation S_{10} ([14]).

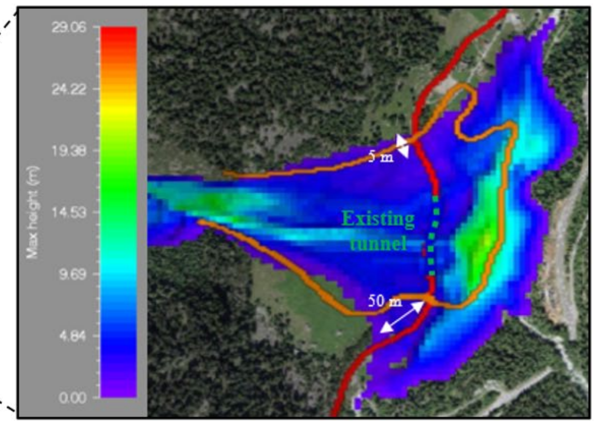


Fig. 7: Covered area: comparison between the snow avalance occurred in 1999 and the simulation S_{10}.

Railway line (North and South stretch)

Existing 131 m long tunnel

Snow avalanche occurred in 1999

Table 1. Numerical simulation S_{10}: main input parameters for release area A_{10}.

Parameter	Symbol	Value
Average slope	θ	38°
Average height	z	2'400 m.a.s.l.
Area	A	566 m^2
Max height	HS_{max}	345 cm
Increase in snowpack height after 3 days of precipitation	$\Delta H3_{gg}$	150 cm
Snow height carried by the wind	H_{sd}	30 cm
Release height	H_d	105 cm
Volume	V	594 m^3

Table 2. Numerical simulation S_{10}: input parameters.

Extension	North side	South side
Snow avalanche 1999	115 m	45 m
Numerical simulation S_{10}	120 m	135 m
Difference	5 m	90 m

Numerical results obtained from S_{10} simulation are given in Fig. 8 a-b-c showing the path followed by the snow avalanche together with the snow height along the flow, the maximum velocity and the pressure. To the North side of the existing tunnel the maximum snow height is approx. 4.6 m with a pressure equal to 300 kPa, while to the South side maximum snow height is about 3.0 m with a pressure equal to 150 kPa. The maximum velocity reached along the entire path is estimated to be 50 m/s, ranging between 15 m/s and 35 m/s both at North and South side of the existing tunnel. All these data will provide the design basis for the intervention measures described in the following. Details concerning all the numerical simulations $S_1 \rightarrow S_{27}$ are provided in [14].

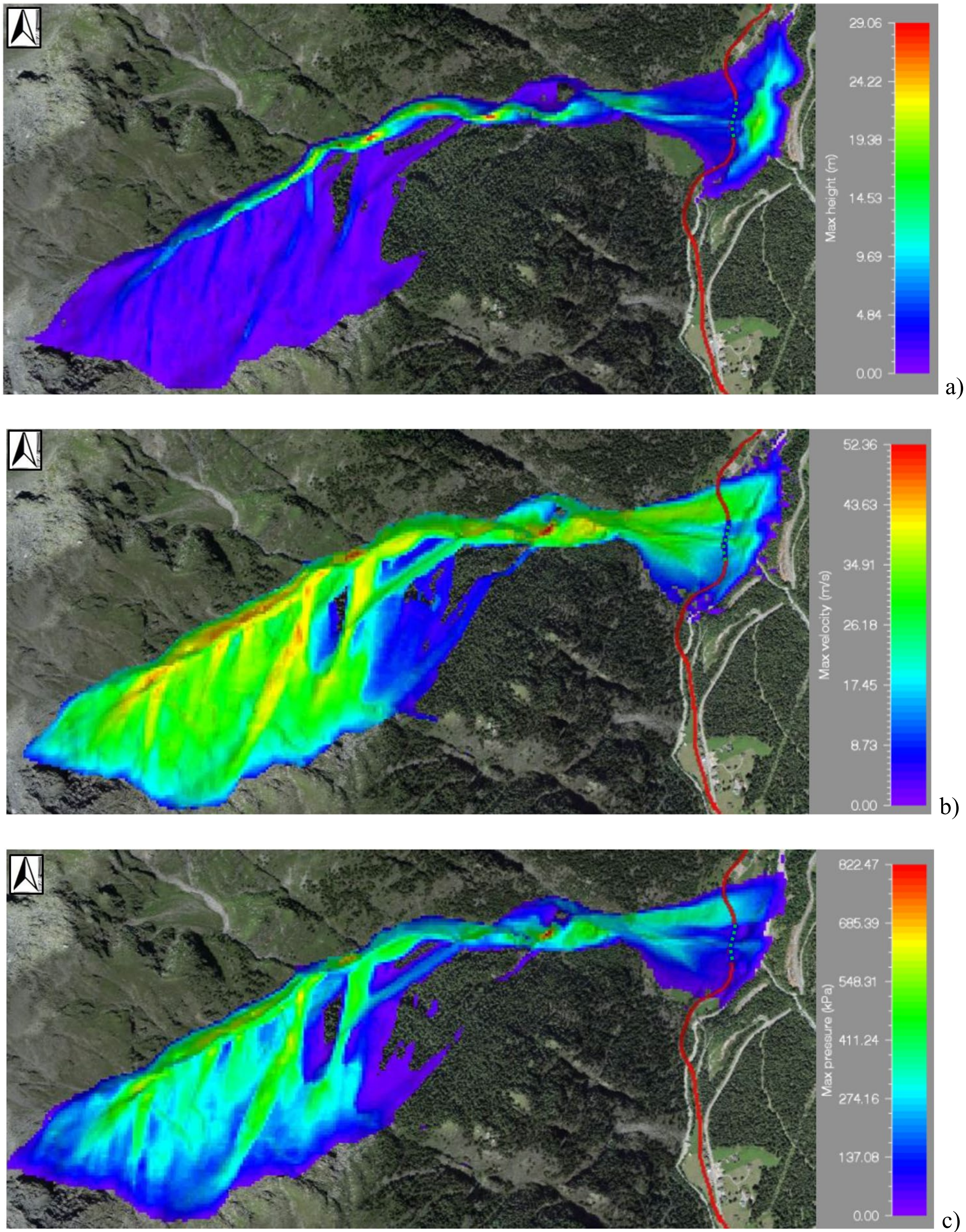


Fig. 8: Results of the numerical simulation S_{10} in terms of a) snow height; b) snow velocity and c) pressure (modified from [14]).

4. Intervention measures

Based on the numerical results described above, some alternative intervention measures are proposed to minimize the hazard raising by the snow avalanches on the railway of the Blattbach area. An extension of the tunnel by two artificial concrete tunnels built at the North and South portals is proposed in Section 4.1. The installation of flexible structures is proposed as second option in Section 4.2, while earth- compacted embankment, or crib walls realized along the slope are suggested in Section 4.3. Finally, these solutions are analysed and compared in terms of efficiency and costs as shown in section 4.4.

4.1. Protection concrete tunnel (option n.1)

The first intervention measure consists of extending the tunnel both at North and South side to cover the areas where protection from snow avalanche with pressures greater than 3 kPa is necessary. As shown in Figure 5, an extension of 110 m to the North and 65 m to the South portal is considered as the minimum length to fulfil the above prescription (Fig. 9). The maximum snow pressure, height and velocity given by the numerical simulations allowed to design the concrete structure as an extension of the existing 131 m long tunnel (Fig. 10).

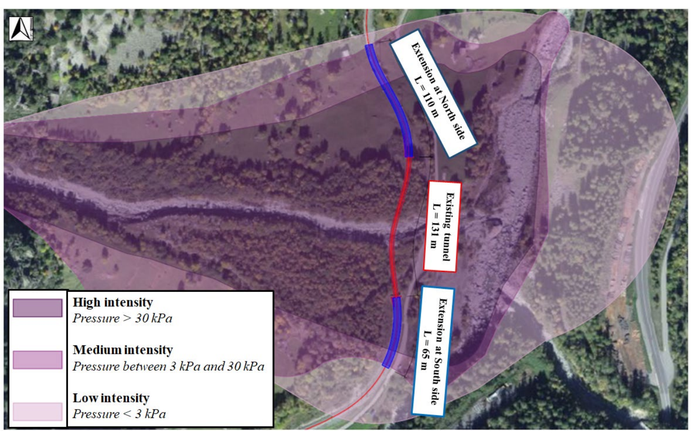


Fig. 9: Plan view of the protection tunnel at North and South portal (modified from [12]).

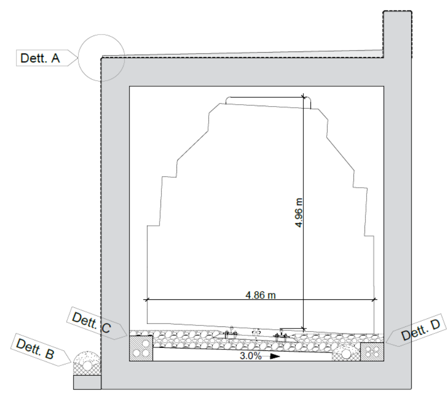


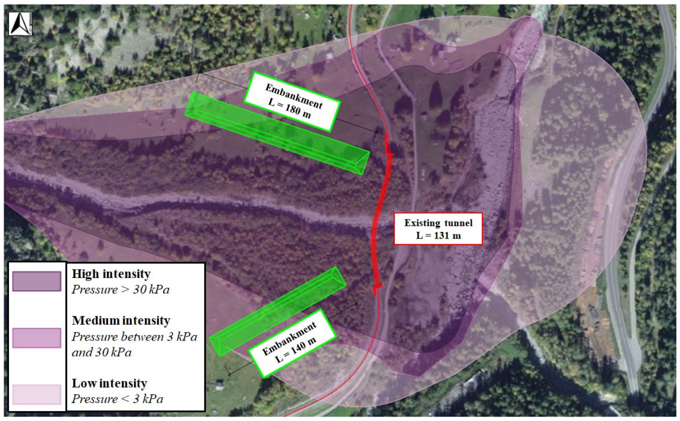
Fig. 10: Tipological section of the concrete structure.

4.2. Flexible retaining structures (option n.2)

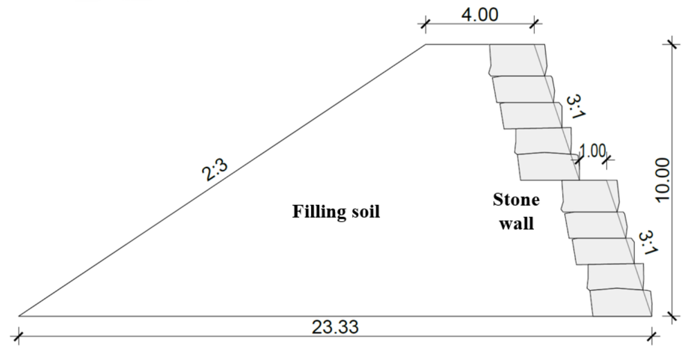
The second intervention measure is represented by avalanche nets as an active measure installed in areas prone to avalanche triggering. These elements would make it possible to avoid triggering the snow avalanches. Among the 27-release areas shown in Fig. 5, based on numerical runout simulation, just the first fifteen could arise snow avalanches covering the railway line. Consequently, the proposed nets should be positioned within this area and designed in terms of net height and spacing, depending on the altitude, slope of the ground. Details are provided in [14].

4.3. Earth-compacted embankment (option n.3)

The last alternative intervention measure mainly consists of bioengineering retaining structures that nowadays represent a widespread solution in civil engineering practice ([18]). The construction of two soil-compacted dams along the slope is proposed, one to the North and one to the South, to divert the snow avalanche path on the existing tunnel. Figure 11a shows the plan view and the positioning of the embankments together with their length to guarantee protection from 30-years avalanches with strong and medium intensity. A 180 m long dam is proposed to the North side, while a 140 m long embankment is proposed to protect the South side. The dimensions of the North dam are given in Fig. 11b, while more details are given in [14].



a)



b)

Fig. 11: a) Plan view of the dams at North and South portals ([14]). b) Tipological section of the North side embankment (dimension in meters).

4.4. Analytical comparison

All the above solutions have been compared and weighted in terms of costs, environmental impact, safety level, feasibility, and durability by assigning a score ranging between 1 (good) and 3 (poor), as shown in Table 3. The best variant is the first one and, although it is not the cheapest solution, it has a significantly lower environmental impact than the other ones. The second variant, both in terms of construction and cost-effectiveness, is not favourable since there are many detachment areas to be protected by active works and would therefore require the installation of many alignments of avalanche barriers. Moreover, its durability and maintenance are critical aspects as the lifespan of the avalanche nets is about 40 years, and in case of replacement the work is very costly. Finally, the critical point of the third variant is the environmental impact, as the dams, due to their large sizes, need a deforestation to be realized with additional unfavourable effects in terms of snow avalanches hazard.

Table 3. Comparison between the proposed intervention measures.

Parameter	Weight	Option n.1	Option n.2	Option n.3
Cost saving	35%	2	3	1
Environmental impact	35%	1	2	3
Safety	10%	1	2	2
Feasibility	10%	2	3	1
Durability/maintenance	10%	2	3	1
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Total	100%	1.55	2.55	1.80

5. Conclusion

The present research highlights the importance of numerical modelling as a key tool to design effective intervention measures aimed to minimize the snow avalanche hazard. Numerical simulations were performed and compared to the 30-years snow avalanche occurred along the Blattbach railway line, allowing to design different intervention measures to protect human lives and infrastructures. The proposed solutions were analysed and compared to identify the better one.

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engineering course, aiming at strong professional orientation and closely linked to professional practice of its Bachelor program. In this frame, the present research takes its first steps from real practical problems, inspired by the professional field, and investigates solutions by applying acquired competences during individual academic path.

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