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Assessment of the Perchertal avalanche in Tyrol, Austria

Tayfun KURT*
Department of Forest Construction and Transportation, Faculty of Forestry, İstanbul University, Bahçeköy, İstanbul, Turkey

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Abstract: The present study has been conducted to analyze the Perchertal avalanche area near Bärenkopf Mountain, which has several avalanche-prone areas on its slopes, within the area of Pertisau, Tyrol, in Austria. The main focus is on identifying the characteristics of the avalanche process itself to determine the potential risk to endangered objects, which include an important road and a hotel. Another focus is to evaluate the current local hazard map. Based on the dynamic avalanche models (Samos-AT, Ramms), several important action parameters such as impact pressure, avalanche velocity, and run-out length of the Perchertal avalanche track are presented and discussed. A variety of potential avalanche scenarios are presented to construct a picture of the potential threats of this specific avalanche area. Assuming accurate simulation results, suitable technical protection measures are described and combined with a cost-benefit analysis to determine the most economically efficient alternatives.

Key words: Avalanche control, simulation, protection measures, Samos-AT, Ramms

1. Introduction

Avalanches are natural phenomena that can cause serious damage to settlements, properties, and transportation facilities and infrastructure such as railways and main roads (Höller, 2007; Sauermoser, 2008; Holub and Fuchs, 2009; Simonson et al., 2010). Importantly, avalanches can also cause fatalities. For example, while crossing the Alps in 218 BC, Hannibal's army lost about 18,000 men, 2000 horses, and several elephants to landslides (Ganju and Dimri, 2002). On 4 March 1910, 62 workmen were killed in an avalanche accident on the Canadian Pacific Rail line at Rogers Pass, British Colombia (Stethem et al., 2003; Schaerer, 1987). The Galtür avalanche, which was the worst modern avalanche disaster in Austria in the last 40 years, killed 31 people in 1999 (Keiler et al., 2006).

In the Alps, avalanches constitute a widespread hazard potential in areas where people live and tourists from all over the world come for skiing. The authorities are aware of the damages that can be caused by avalanches, and they are striving to avoid future avalanche damages. In fact, dealing with avalanches and strategies to avoid the effects of avalanche events have a long tradition in the Alps (Keiler et al., 2006). For example, Austria started to work on avalanche protection in 1880 by stabilizing the snow pack and by building types of snow rakes to be used on starting zones in Tyrol and Vorarlberg (Sauermoser, 2008), and in the second half of the nineteenth century, avalanche management authorities were established in Switzerland (Frutiger, 1980; Keiler et al., 2006). The French avalanche risk management system is generally considered as having been drawn up in the early 1970s, after an avalanche devastated a youth hostel in Val d'Isere in February 1970 and claimed 39 lives (Hervas, 2003). However, the avalanche permanent survey in France began in 1900 for most of the sites, describing each event that occurred at 5000 determined sites in France (Belanger and Cassayre, 2004). Another Alpine country is Italy, in which the various organizations that deal with avalanche hazard forecast and prevention were originally structured in 1983 to form an association called AINEVA (Peretti, 1992; Hervas, 2003), which stands for the Interregional Association for Snow and Avalanches.

In 1884, the Austrian Forest Engineering Service for Torrent and Avalanche Control (WLV) developed public interest services in the Alpine regions (Keiler et al., 2006; Sauermoser, 2008; Holub and Fuchs, 2009). More recently, the WLV has developed avalanche control projects in order to ensure maximum safety for settlements, villages, and transportation routes in Austria. Avalanche risk mitigation includes supporting structures in the release areas, and catching and deflecting dams in the run-out zones (Höller, 2007). Snow sheds, tunnels, hazard zoning, artificial avalanche releases, and redevelopment of mountain forests are also used (Höller, 2007; Keiler et al., 2009).

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* Correspondence: tayfun.kurt@istanbul.edu.tr

One of the high damage risk areas in the Austrian Alps is Perchertal (Figure 1), where 2 snow avalanches have occurred since 1947 (Stepanek and Skolaut, 2001). The current avalanche hazard map is based on 1-dimensional (statistical) avalanche simulation modeling. There is a lack of study on 3-dimensional (dynamic) avalanche simulation modeling and a lack of avalanche risk assessment based on technical protection measures combined with cost and benefit analysis geared towards find an economical solution. The objective of this study was to partially close these gaps by studying a new hazard map with temporal changes in avalanche risk such that changes of the risk-influencing factors have natural, economic, and technical reasons. Therefore, the developments of those factors were regarded separately and their interconnections have been analyzed. When delimiting the new hazard zones for avalanche tracks, traditional methods such as field studies and analyses of previous avalanche events are used as well as simulation models. Therefore, the results of this study might also provide a basis for the implementation of changed delimitation criteria such as avalanche control measures.

2. Materials

2.1. Investigation area

Tyrol, at 467 km^2, is the third largest Austrian province and is the most-visited region with about 43.8 million overnight stays in 2008 (Statistics Austria, 2009). Achensee is a natural lake that is located in the district of Schwaz in Tyrol (Figure 1). Many people live in this community, and there are many hotels due to the large number of tourists who visit the region in the winter.

Figure 1. Administrative districts of Tyrol.

The mountainous area of the region offers ideal conditions for winter activities, but these topographic characteristics create a widespread hazard risk in the region due to possible avalanches. Therefore, guests can be in danger of injury or death due to an avalanche. In this sense, the Perchertal avalanche area has repeatedly been threatening a hotel since 1948 based on a technical avalanche report written by the WLV (Stepanek and Skolaut, 2001). The avalanche path also includes a part of the main road that provides accessibility for a village within the area of Achensee, Tyrol, in Austria (Figures 2 and 3).

2.2. Meteorological data

When using simulation models, major uncertainties result from the use of the input parameters, such as release depth and release extent (Keiler et al., 2006). In order to minimize these uncertainties, meteorological values were provided by the Pertisau weather station (this is the name of the meteorological weather station as well as a settlement area in Tyrol, Austria), which is located 935 m above sea level (Figure 4). The time scale was 100 years (1900–2000) of recorded values. This is understood to be a significant factor when it is considered that the local records of avalanche events do not cover a 150-year period, so the extrapolated 150-year amount of new snow in 3 days was taken instead, in accordance with international practice (Keiler et al., 2006). In addition, large avalanches may be released during storm periods when the accumulated new snow is more than 80 cm within 3 days (Höller, 2007). Meteorological data from the Pertisau weather station showed that the 3-day amount of new snow is 158 cm for Pertisau. In order to ensure maximum safety in terms of the avalanche deposition area, the avalanche release height was assumed to be 1.58 m of snow for avalanche modeling.

2.3. Chronology of avalanche events

Documented observations of avalanche events provide the most reliable information regarding avalanches (Armstrong, 2006). For that purpose, a relevant avalanche report was examined.

The avalanche report of the Perchertal avalanche, which was written in 2001, gives information on avalanches that occurred between 1945 and 1988. All of the avalanches reported, which happened in 1945, 1973, 1981, 1987, and 1988, were of the dense-flow type (Stepanek and Skolaut, 2001). So far, the largest known avalanche occurred in 1973 as a wet-snow avalanche (Figure 5), which was caused by a rise in temperature.

2.4. Official local avalanche hazard map

The official local hazard map of the Perchertal avalanche was drawn in 2001 based on a statistical avalanche-modeling program (Alpha-Beta Model). This map indicates that the hotel and part of the main road that passes in front of it are located entirely in the red zone (Figure 6).

Figure 2. Overview of the Perchertal avalanche tracks.

Figure 3. Overview of the endangered hotel.

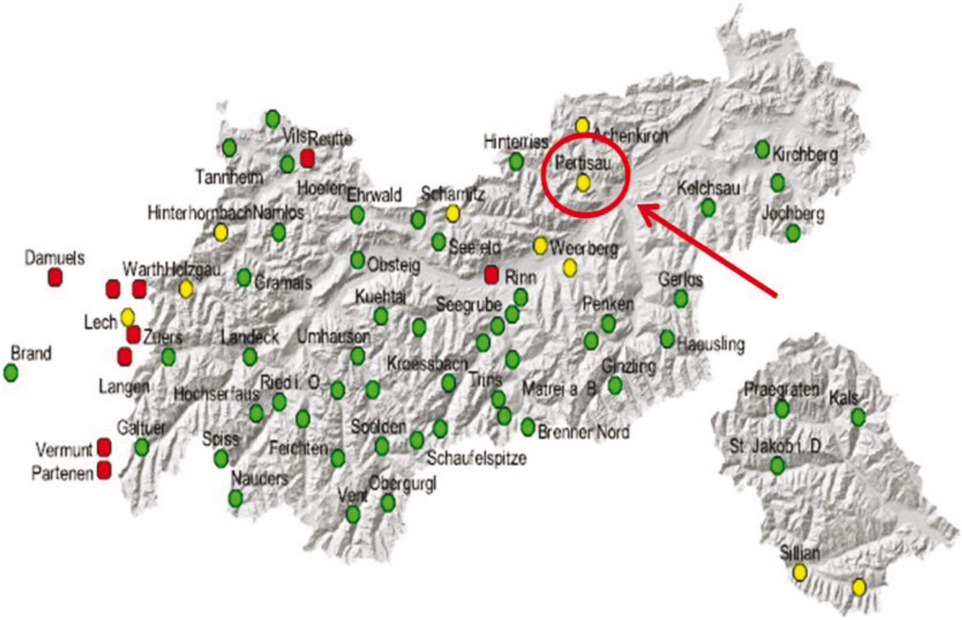

Figure 4. Overview of the location of the Pertisau weather station in Tyrol (Schellander, 2004).

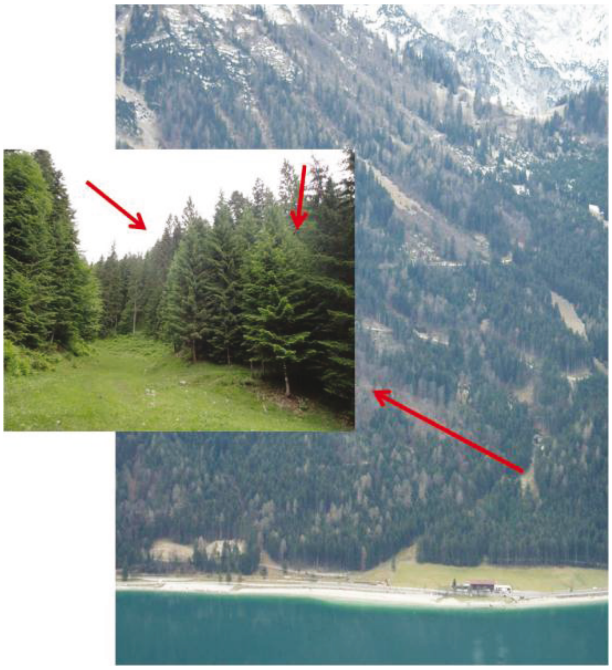

Figure 5. Endpoint of the Perchertal dense-flow avalanche occurring in 1973 (photo: Kurt and Granig).

According to Austrian law, 2 types of avalanche hazard zoning are used to illustrate the situation for endangered areas regarding avalanche hazard (Table 1; Lebensministerium, 2010).

Red illustrates the most dangerous zones on the hazard map (Holub and Fuchs, 2009; Lebensministerium, 2010). No new construction has been allowed inside the red zone. However, the presence of public services such as railways required that avalanche protection construction be performed to prevent possible avalanches or reduce any avalanche damage (Holub and Fuchs, 2009; Lebensministerium, 2010). Thus, some construction is allowed inside the red zone.

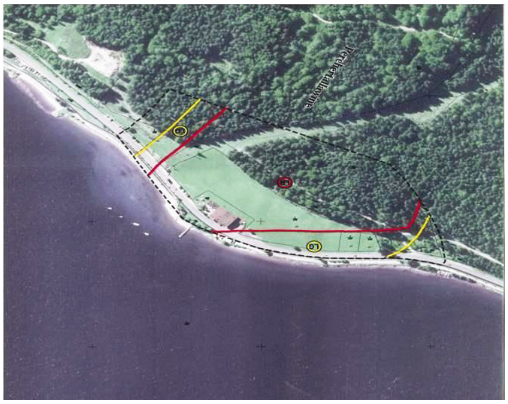

Figure 6. Official local hazard map of the investigation area.

Table 1. Types of avalanche risk zoning used in Austria (Lebensministerium, 2010).

	Avalanche zone	Impact pressure
Return period (150 years)	Yellow	$1 \le P < 10$ k N/m^2
	Red	$P \ge 10$ k N/m^2

Yellow illustrates a hazardous zone but describes a lower avalanche threat. It means that any object that is already located in the yellow zone can be affected by avalanche impact pressure that has a value lower than 10 k N/m^2 (Lebensministerium, 2010). In other words, yellow hazard zones indicate the areas in which a permanent utilization for settlement and infrastructure is possible, but with additional requirements (Holub and Fuchs, 2009).

2.5. Simulation data and parameters

In this study, 2 different dynamic avalanche simulation models were applied (Samos-AT and Ramms) in order to determine the potential risk to the endangered objects in the relevant area.

Samos-AT (snow avalanche modeling and simulation) is a type of simulation model used for dense- and powder-snow avalanches (Granig et al., 2009). It describes both the dense-flow layer and the powder-snow layer of an avalanche, as well as the interaction between them (Granig et al., 2009). Especially dense-flow avalanche scenarios have been calculated with Samos-AT. The input parameters used for the simulations are shown in Table 2. Avalanche flow velocity, flow height, and avalanche impact pressures were provided using Samos-AT.

Another simulation model, Ramms (Christen et al., 2011), was used in order to compare the accuracy of the results. Dense-flow avalanches have also been calculated with Ramms, which was developed at the Snow and Avalanche Research Department (SLF) of the Swiss Institute in Davos (Christen et al., 2011). The model is a development of the 1-D numerical model Aval1D (Christen et al., 2011). The inputs shown below were used to simulate avalanche scenarios with the Ramms model (Table 3).

Table 2. Input parameters used for the Samos-AT simulation model.

Input parameter	Samos-AT
Flow density [kg/m^3]	200
Particle diameter [m]	0.0008
Flow resistance (forest)	0
Entrainment [cm]	0
Avalanche release height [m]	1.58

Table 3. Input parameters used for the Ramms simulation models.

Input parameter	Ramms
Flow Density [kg/m^3]	300
Friction law	Voellmy fluid
Annularity of avalanche	100 years
Avalanche release height [m]	1.58

3. Results

3.1. Interpretation of avalanche frequency

Vegetation analysis can be used to survey past avalanches and to estimate the frequency and intensity of snow-slide events for specific avalanche path locations and time periods of interest (Burrows and Burrows, 1976; Carrara, 1979; Mears, 1992; Jenkins and Habertson, 2004; Casteller et al., 2007; Bebi et al., 2009; Simonson et al., 2010). To achieve this goal, a field study was done in order to define the vegetation types and to create a forest map of the relevant area in the date range 18.05–21.05.2011. The age classifications of tree vegetation types and soil regimes were defined empirically and recorded for the whole forest because it was thought that the forest stand structure might be a source of relevant information for the avalanches.

Tree trunks may grow in a tilted position, typically pointing down the slope in the direction of avalanche flow, and "J"-shaped trunks may develop in response to repeated impacts and tilting (Weir, 2002; Simonson et al., 2010). This situation has been observed on avalanche paths (Figure 7), and this relevant information has been assumed to represent silent witnesses because descriptions of stand structure by age classification, tree heights, soil regime, canopy cover, and so on can define whether the stand has been affected by a recent avalanche or was affected by an earlier one (Figure 8).

As a result, the vegetation type can be described as a moderately forested area. High altitudes are usually dominated by dwarf mountain pine (*Pinus mugo)*, while spruce (*Picea abies*), beech (*Fagus sylvatica*), larch (*Larix deciduas)*, and fir (*Abies alba*) are visible in the lower areas.

3.2. Slope analysis

Slope incline is one of the most significant terrain characteristics in determining avalanche-prone areas. According to Miklau and Sauermoser (2011), avalanches most commonly occur on slopes of between 28° and 55° (Table 4). Therefore, a classification of inclination was performed (Figure 9). A total of 9 avalanche release zones were illustrated based on slope analysis and information reported about previous avalanches.

3.3. Avalanche modeling

Two different dynamic avalanche simulation models were applied for this study. The numerical simulations were based on a digital terrain model (DTM) that was created with an airborne laser-scanner measurement and thinned to a 5-m grid in order to achieve high accuracy.

Figure 7. "J"-shaped trunks due to avalanche.

Nine possible avalanche scenarios were simulated as dense-flow avalanches using the Samos-AT model, and their avalanche pressures differed due to different avalanche run-out zones. The results illustrated that 3 avalanche scenarios from 3 release zones (R1, R2, and R3) constituted particularly risky situations for the hotel and the main road. Therefore, the 3 possible avalanche scenarios were also simulated separately as dense-flow avalanches using Ramms. Because we wanted to compare the results with the Samos-AT dense-flow results, the maximum pressures, flow heights, and velocities of avalanche flows were all calculated.

3.4. Determination of objects at risk

The objects and persons described below are endangered by the Perchertal avalanche flow area.

· Two buildings: the hotel and an apartment building nearby where workers can stay overnight if there is damage from an avalanche. The hotel can host 50 tourists per night.

· The part of the main road that passes in front of the hotel could be buried under an avalanche. The endangered part of the main road is 500 m long and 6 m wide. If this road were buried by snow, it would take 2 days to reopen.

3.5. Suitable avalanche protection measures

Three types of avalanche protection in the deposition zone, steel snow bridges, a deflecting dam, and a catching dam, were evaluated to secure the Perchertal avalanche. The most effective but most expensive solution for the Perchertal avalanche would be to build steel snow bridges in the release zones, which would prevent a snow motion function before an avalanche is triggered (Höller, 2007). However, environmentalists have complained about this measure, maintaining that these types of metal structures spoil the aesthetics of the natural environment. However, despite these negative views, according to the local director

Figure 8. Discrete boundaries on the avalanche track.

of the WLV office in Schwaz, snow bridges are used most often for avalanche protection in Austria. Therefore, snow bridges to prevent possible avalanche releases from R1, R2, and R3 were evaluated first.

Building a catching dam can be acceptable as a permanent solution if there is sufficient available space in the deposition area (Johannesson et al., 2009). A catching dam could ensure a maximum safety level for the hotel and the part of the main road that is vulnerable.

Another avalanche mitigation measure is building a deflecting dam in the deposition area, which would protect the hotel by diverting avalanche flows before they damage the structure.

3.6. Avalanche simulation results

As mentioned above, the results illustrate that the 3 dense-flow avalanche scenarios from the 3 release zones represent especially risky situations for the hotel and the main road (Figure 10). For the maximum scenario, the building (hotel) was slightly affected by the simulated dense-flow avalanche (Figure 11).

3.6.1. Risk scenario R1

In scenario R1, the potential snow accumulation is 62.7 m^3, the rounded inclination is 46°, and the release zone covers a total area of 3.1 ha according to Arc-map calculations. The area has a rocky ground surface as well as a dominant vegetation type, which is dwarf mountain pine (*Pinus mugo*). According to information received from inhabitants in Pertisau, R1 does not usually trigger avalanches. Moreover, it can only trigger an avalanche in the event of extraordinary weather conditions (e.g., heavy snowfall and strong winds from the northeast).

Table 4. Classification of inclination in terms of avalanche risk (Miklau and Sauermoser, 2011).

Inclination (°)	Risk of triggering avalanche
0–28	Low risk
28–35	Middle risk
35–55	High risk
55–90	Low risk

3.6.2. Risk scenario R2

The potential snow accumulation of scenario R2 is 58.3 m^3, the rounded inclination is 35°, and R2 covers a total area of 3.1 ha. R2 can be assumed to be the most active release zone due to frequent, though usually minor, avalanche releases every year. This situation is due to its slippery ground surface and the presence of less surface vegetation, and the chronology of avalanche events supports this thesis. Thus, R2 is the most frequent avalanche scenario among the 3.

3.6.3. Risk scenario R3

The biggest avalanche release zone is R3 on Bärenkopf Mountain. The potential snow accumulation on R3 is 139.6 m^3, the rounded inclination is 39°, and R3 covers a total area of 7.2 ha based on GIS calculations. The accumulation of snow triggers avalanches that are different from the Perchertal avalanches in terms of their tracks. R3 also seems to be an active release zone based on evidence from the silent witnesses on the avalanche tracks that are affected by minor wet-snow avalanche releases every year (Figure 12). These silent witnesses represent the most dangerous dense-flow avalanche scenario for the hotel and the main road because they can come from a wide form of avalanche tracks, crash into the hotel, and continue on into the lake. In the worst-case scenario, the highest impact pressure on the hotel was calculated at about 3 kPa (Figure 11).

4. Discussion and conclusions

In comparing the release zones, the development of the risks of the 3 studied avalanche tracks differ considerably. In the following section, those different developments are

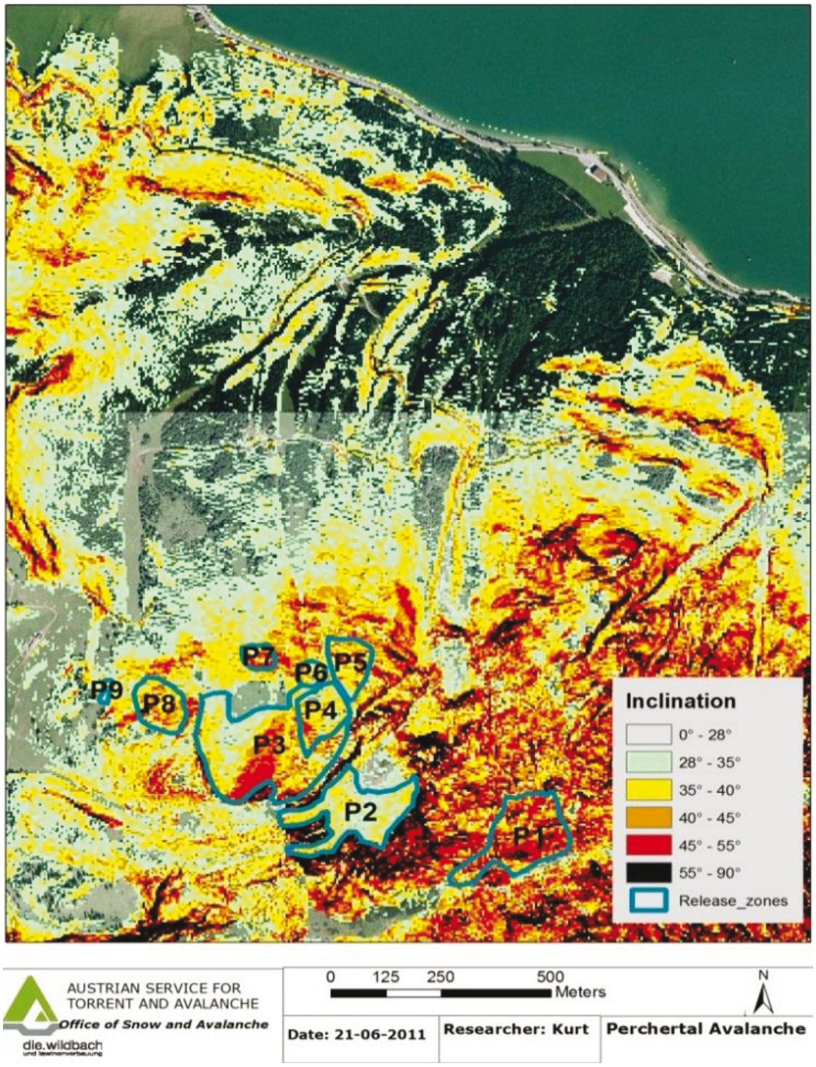

Figure 9. Avalanche release zones based on slope analysis.

analyzed with respect to the factors influencing the risk, such as the various types of mitigation measures.

In this investigation, protection measures were evaluated that take a hazard map of the relevant area and acceptable risks of the endangered area into consideration. According to the new avalanche hazard map based on the simulation results and avalanche chronology, the hotel is located entirely in the yellow zone, which covers a widespread area on both the right and left sides of the building (Figure 13). There are no avalanche control structures in either the release or deposition area, except in the densely forested area; therefore, structures in both the release and the deposition area were considered as options to cope with possible future damages caused by the avalanches.

In the case of a powder-snow avalanche, the hotel can remain entirely in the yellow zone based on results from the Samos-AT model. However, as mentioned earlier, powder-snow avalanches are unrealistic scenarios, which means building a control structure is not essential.

Steel snow bridges can be assumed to be the most effective permanent technical protection measure to ensure maximum safety of the endangered area. Therefore, in order to prevent avalanches starting from R1, R2, and R3, snow bridges were planned. Due to R3's large area, a combination of avalanche protection measures (steel and wooden structures along with afforestation activity) were evaluated in order to reduce the costs of the work. For example, R3 has a smooth ground surface that is covered by grass and some existing trees. For this reason, 40% of R3 was assumed suitable for afforestation. However, minor avalanches might not let saplings grow without any support structures on the release zone. Therefore, 40% of the area was evaluated for building wooden structures.

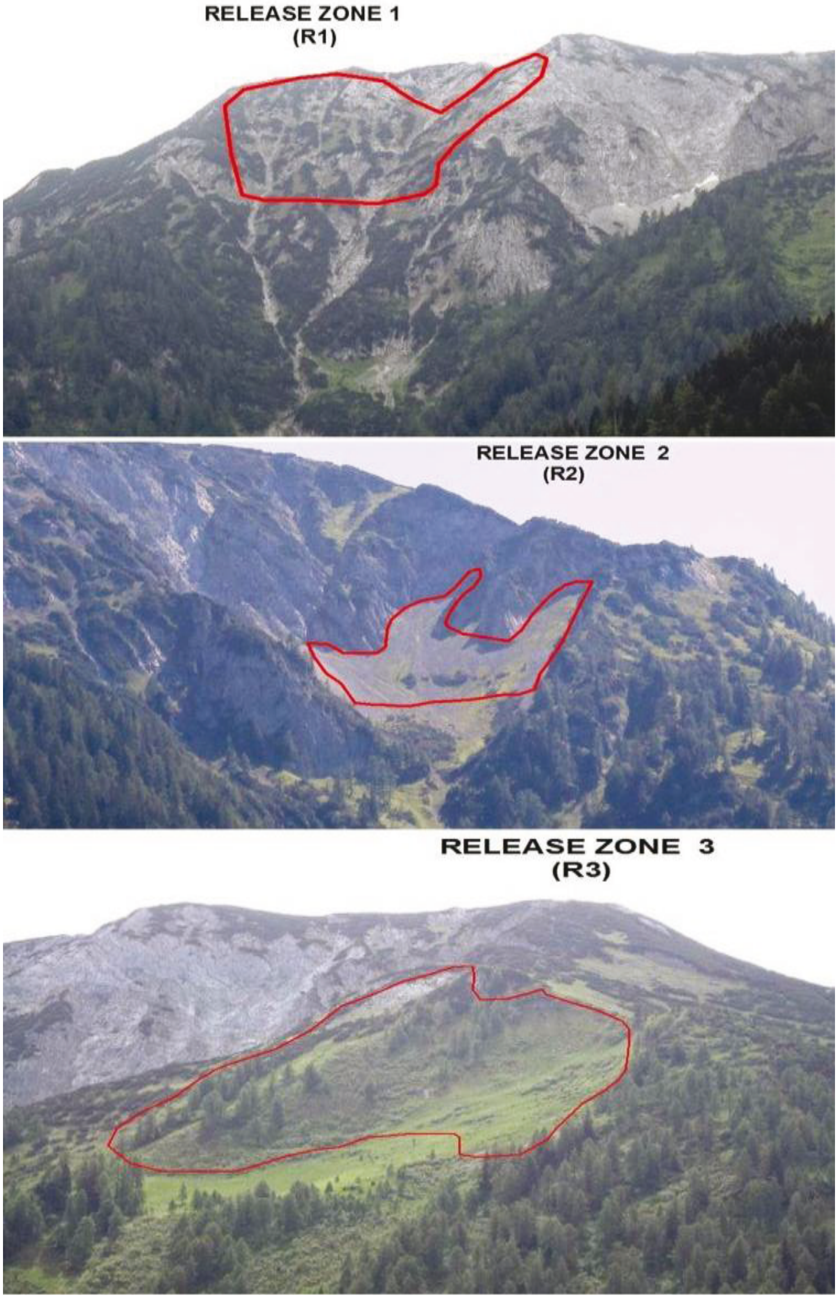

Figure 10. Overview of the avalanche release zones.

The rest of the area (20%), which is very steep and rocky, was evaluated for building steel snow bridges. In addition, afforestation is not a good method to prevent avalanches for R1, and especially for R2, due to the rocky ground surface; trees might not grow under these rocky soil conditions even with minor avalanches. In this case, the timberline will drop below the rock or gravel zone. In spite of these planned combined measures, calculations showed that the price of protection is still high.

A blasting mast is a type of structure used to create artificial avalanches as a temporary avalanche risk reduction measure. Creating an artificial avalanche by using a blasting mast system was thought to release the Perchertal avalanche under controlled conditions as the use of explosives frequently triggers smaller, less destructive avalanches. This technique involves the triggering of explosives by detonating charges above the snow surface. Remote-controlled installations are placed in specific locations that generate an

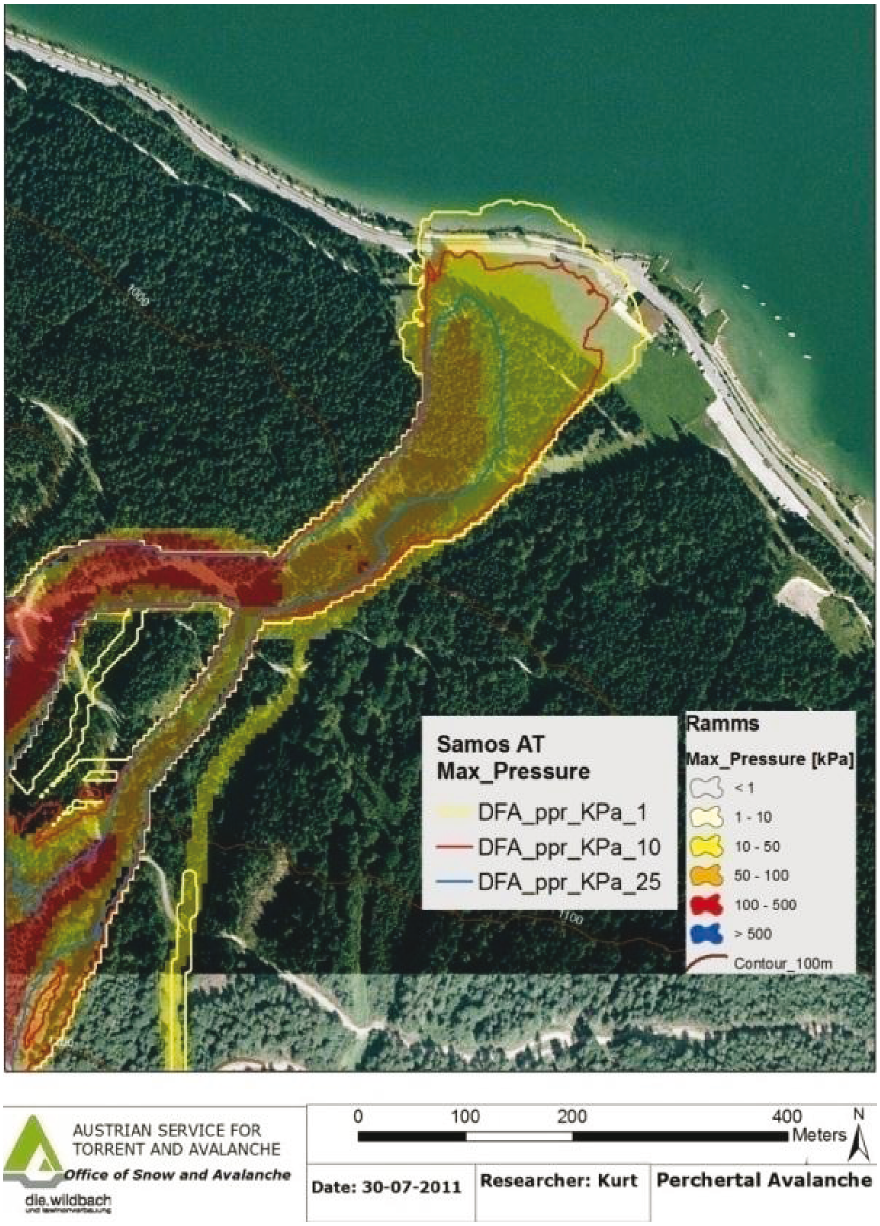

Figure 11. Overview of the maximum scenario of the Perchertal avalanche.

air blast above the snow pack in the avalanche start zone. Avalanche blasting systems were considered for all 3 release zones as another temporary avalanche protection measure. However, only minor avalanches can be tolerated using this system. In other words, in areas with human residences, even a small probability of a larger avalanche is unacceptable.

Building a catching dam can be an acceptable solution if there is sufficient available space in the deposition area (Johannesson et al., 2009). This partly depends on the economic situation of the authorities and their decisions. For example, if both the hotel and the vulnerable part of the main road needed to be protected against possible future

Figure 12. Overview of release zone 3.

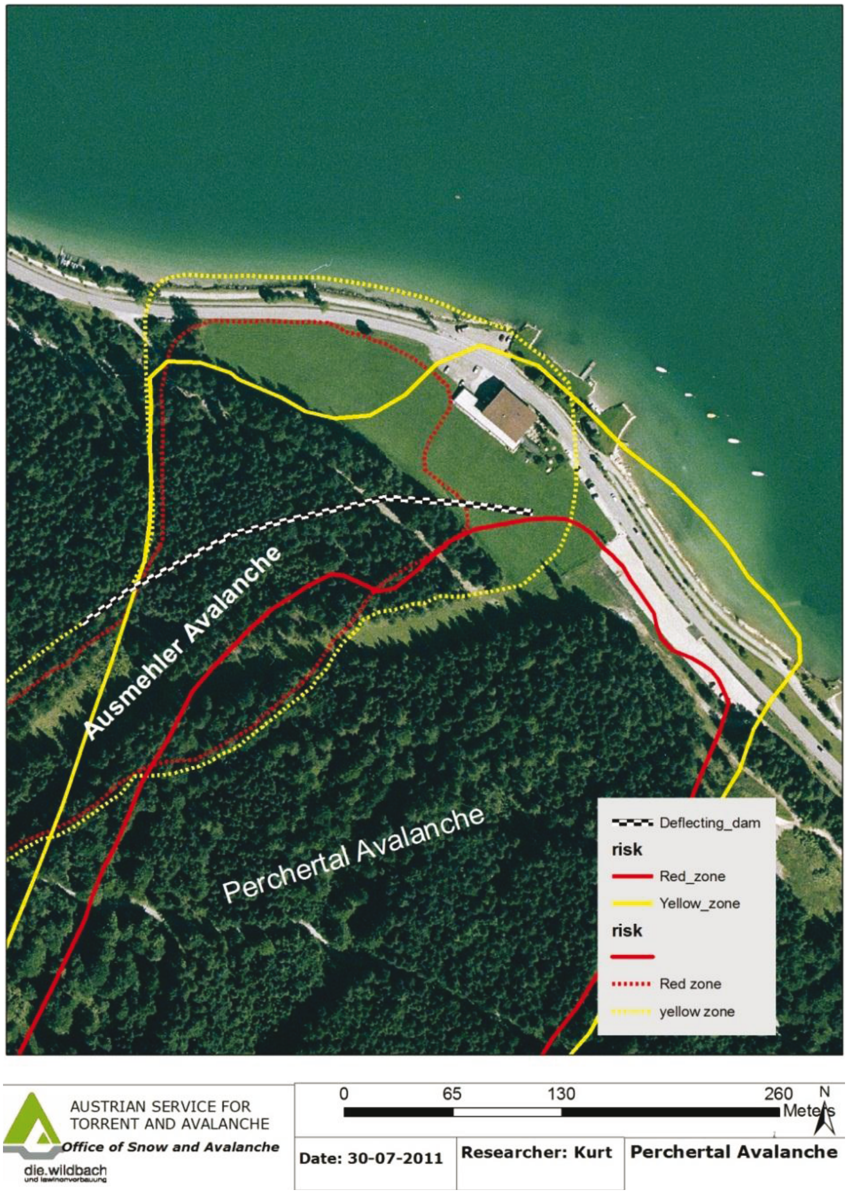

Figure 13. Overview of new avalanche hazard map based on the simulation results.

avalanches, a catching dam could be recommended, which would ensure the maximum safety level for the hotel and the road. During the field studies, there was no intense traffic on the main road and, according to the chronology of avalanche events, none of the avalanches that had occurred had ever reached the main road or destroyed the hotel. This means that protection for the main road is not immediately essential. Moreover, if a catching dam were built, it would be very expensive due to the large dimensions needed, about 485 m long.

Deflecting dams can be used to divert avalanches away from objects at risk (Johannesson et al., 2009); therefore, it was assumed to be one of the alternative solutions for this investigation as there was enough space to divert avalanches away from the hotel on both the left and right side. A deflecting dam was designed in the deposition area to prevent damage from the Perchertal avalanche, taking into account the avalanche velocities and flow depths as well as the deflecting angle of avalanche flow. Building a deflecting dam seems to be the best solution among the choices, based on cost and benefit analysis. Therefore, it is recommended as the solution for this avalanche problem.

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