ANALYSIS OF THE HAZARD CAUSED BY ICE AVALANCHES FROM THE HANGING GLACIER ON THE EIGER WEST FACE

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ABSTRACT: The Eiger hanging glacier is located in the west face of the Eiger in the Bernese Alps (Switzerland). Large ice avalanches, especially if they trigger secondary snow avalanches, endanger parts of the ski area Jungfrau and the Jungfraujoch railway. The latter leads to the Jungfraujoch, one of the top tourist destinations in Europe. In autumn 2015, the formation of a crevasse immediately behind the front of the hanging glacier was detected, indicating an impending icefall with a maximum ice volume of 80'000 m³. Consequently, a hazard analysis was performed for four different scenarios with varying ice volumes and snow conditions. The analysis showed that a 100 m high rocky ridge situated in the main flow direction of the avalanches plays a crucial role due to its braking and deviating effect. Closure plans were prepared for the four scenarios investigated. The railway station is especially endangered in the extreme scenario assuming an ice volume of 80'000 m³ and unstable snow conditions. We therefore recommended to trigger avalanches below the hanging glacier artificially after snowfall events and to install an early warning and alarm system to minimize the closure times for the railway and ski area.

KEYWORDS: Risk management, Ice avalanche, Avalanche simulation, Hazard assessment.

1. INTRODUCTION

The Eiger hanging glacier is located on the west face of the Eiger in the Bernese Alps (Switzerland). The hanging glacier is an unbalanced terrace glacier with wedge fracture at an elevation between 3500 and 3200 m a.s.l. (Pralong and Funk, 2006) and with a mean surface angle of 35° (Fig. 1). The front of the glacier is 200 m wide and 40 m high (Fig. 2). The usual ablation zone of the hanging glacier is the front, where ice lamellas with typical volumes of less than 10'000 m^3 break off periodically. Large ice avalanches, especially if they trigger secondary snow avalanches, endanger parts of the ski area Jungfrau and the railway, which leads through a 7 km long tunnel through the Eiger to the Jungfraujoch. The railway was opened in 1912. The Jungfraujoch located at 3454 m a.s.l. is one of the top tourist destinations in Europe and is yearly frequented by one million visitors. On peak days up to 5000 visitors use the railway. The area around the railway station Eigergletscher is particularly exposed.

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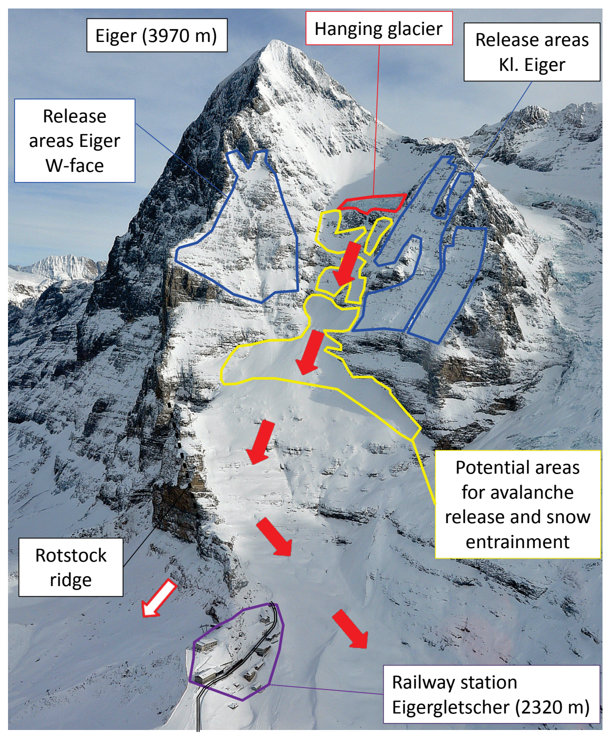

Fig. 1: Overview on the Eiger with the hanging glacier in the W-face, possible flow paths of ice avalanches and location of the Eigergletscher railway station.

The hanging glacier has been monitored with an automatic camera since 1996. In autumn 2015, the formation of a crevasse immediately behind the front was detected, indicating an impending failure with a maximum ice volume of 80'000 m³. The SLF was consequently mandated to evaluate the hazard situation by the Jungfrau Railways and to propose safety measures if necessary. GEOPRAEVENT installed a monitoring system and GEOTEST elaborated a safety concept.

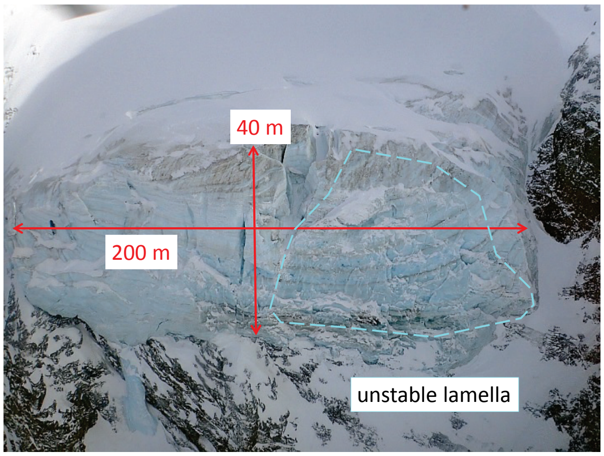

Fig. 2: Front of hanging glacier on Eiger W-face (18 January 2016).

2. TOPOGRAPHICAL AND AVALANCHE SITUATION

Ice avalanches which break off the hanging glacier first flow over 400 vertical meters through a 45° steep and 100 m wide gully. The gully is interrupted by small cliffs, which favour the formation of powder snow avalanches. Below the steep channel the topography widens and consists of a 35° slope with a surface area of 90'000 m^2. This is the main release area where ice avalanches can trigger secondary snow avalanches. Additional release areas for snow avalanches exist in the steep rock faces of the Eiger and Klein Eiger, which are separated by rocky ridges from the main avalanche path below the hanging glacier (Fig. 1). These release zones are rather wind exposed and snow is often blown off. During snowfall or warming periods loose snow avalanches release, which disturb and stabilize the snowpack in the main release area for secondary snow avalanches. Our analysis showed that the rocky Rotstock ridge situated in the main flow direction of the avalanches plays a crucial role, due to its braking and deviating effect (Fig. 3). The elevation of the ridge above the surrounding terrain varies between 55 and 110 m in the main impact zone. The ridge deflects avalanches southwestwards towards a glacial depression. In the absence of the rocky Rotstock ridge avalanches would flow straight on northwards. The railway station Eigergletscher situated at 2200 m a.s.l. is at the northern margin of the flow path of ice avalanches from the hanging glacier.

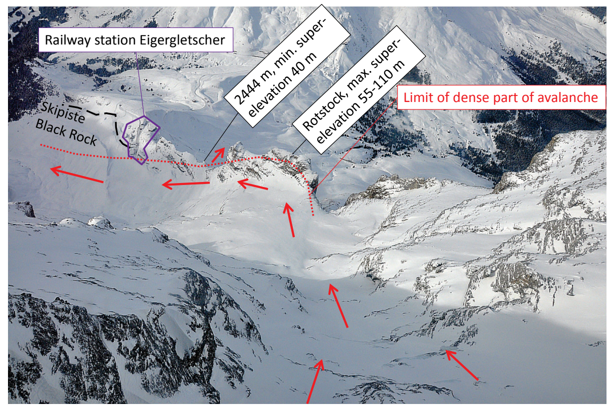

Fig. 3: View from hanging glacier along flow path with the Rotstock ridge.

3. HISTORICAL ICE AVALANCHES AND INVESTIGATED ICE FALL SCENARIOS

The record of historical icefall events is incomplete, especially before 1980. We assume that ice avalanches smaller than 10'000 m^3 often went unnoticed. Larger ice avalanches were observed in 1982, 1990 and 1991 (Raymond et al., 2003). The 1990 event happened in summer and involved an ice volume of approximately 100'000 m^3. The ice avalanche bypassed the area of the railway station Eigergletscher by 65 m. Only minor damage such as broken windows occurred at the railway station. Since the construction of the railway in 1898 it is unlikely that a large ice avalanche occurred in winter time, releasing additional snow masses. During this time period of 117 years the thickness of the hanging glacier has decreased slightly but the geometry of the front of the hanging glacier has not changed much. A detachment of the whole hanging glacier with a maximal ice volume of 1 Mio. m^3 is considered to be unlikely in the near future. In our study we evaluated the following four scenarios:

1. Icefall of 10'000 m^3 without snow entrainment (summer and winter with stable snowpack)

2. Icefall of 10'000 m^3 with snow entrainment (winter with unstable snowpack)

3. Icefall of 80'000 m^3 without snow entrainment (summer and winter with stable snowpack)

4. Icefall of 80'000 m^3 with snow entrainment (winter with unstable snowpack).

4. AVALANCHE DYNAMICS CALCULATIONS

The simulation of ice avalanches falling from a hanging glacier is complex. In summer with a snow free topography the detaching ice mass bursts into smaller pieces of ice and falls as a dense avalanche. Because of the steep topography the formation of a powder cloud is likely, especially for large ice volumes. If the topography is snow covered, the ice avalanche can entrain part of the snow cover or release secondary snow avalanches and will exhibit smaller friction forces. As a consequence a combined snow/ice avalanche has a greater mass, an increased powder part and a longer runout.

We applied the two-layer RAMMS-RKE model which has been implemented in the research version of the RAMMS (Christen et al., 2010) avalanche dynamics program. The two layer model consists of an avalanche core and a powder cloud. The cloud is treated as an inertial flow arising from the avalanche core (Bartelt et al., 2015). The density of the core is not constant – allowing dilute, disperse and dense flows. The core of the avalanche is driven by the gravitational acceleration in the slope-parallel direction. The mass exchanges in the mixed flowing avalanche system are snow entrainment into the avalanche core, volume and mass blow-out of ice-dust from the core into the powder cloud and direct air entrainment. The shearing in the core is considered with a Voellmy-type ansatz where the Coulomb friction μ and turbulent friction ξ depend on the configurational energy content of the core (Bartelt et al., 2015) implying that the friction values μ and ξ are adjusted to variations in the flow density. Central to the model equations is the inclusion of the free mechanical energy of the avalanche core which is the sum of the energy of the random granule motions and density changes (Buser and Bartelt, 2015). The model parameter α describes the production rate of the free mechanical energy in relation of the total shear work. The kinetic energy part is considered with the parameter β which is very dependent on the snow temperature. We applied the parameters $\alpha = 0.06$ and $\beta = 0.8$ in the simulations. For the avalanche core at rest we used a density $\rho_0 = 850$ kgm^{-3}, $\mu_0 = 0.55$, $\xi_0 = 2000$ ms^{-2} and an ice temperature of -10° C.

A large uncertainty in the simulation is the treatment of ice avalanches flowing over a snowpack. Observation show that if the snowpack is very stable the avalanche flows over the snowpack without entraining relevant snow masses. If the snowpack is unstable a secondary slab avalanche can be triggered and if the snowpack is loose the avalanche entrains snow. We approached this problem with the RAMMS entrainment module (Margreth et al., 2011). In scenarios 2 and 4 we assumed a potential entrainment height of 1.0 m, a snow density of 200 kgm^{-3} and a snow temperature of -5° C along the whole track of the avalanche. We used the velocity driven entrainment law implemented in RAMMS with an erodibility coefficient k = 0.5 kgm^{-3}. This value defines the intake rate of snow by the ice avalanche. A value k > 0.2 kgm^{-3} ensures that snow is primarily taken in at the front of the avalanche, facilitating the formation of the powder cloud. In the simulations the powder avalanche forms quickly after release and the ice-avalanche core entrains practically the whole snowpack along the entire path.

The computational grid was generated from a Digital Elevation Model with a 2 m resolution. The simulation resolution is 10 m. First simulations showed that the braking and deviating effect of the rocky ridge of the Rotstock is not satisfactorily included in the model. Most of the avalanching snow overflowed the rocky ridge. We would expect a clear flow separation. We think that the powder cloud overflows partly the rocky ridge and that the core is deviated southwestwards. In order to respect this deficiency we introduced an area with an increased friction along the rocky ridge ($\mu = 1.0$ instead of 0.55 and $\xi = 100$ instead of 2000 ms^{-2}). The adapted friction parameters slow down the avalanche and increase the deviating effect of the rocky ridge.

The RAMMS simulations show the following results (Tab. 1):

In **scenario 1** an ice avalanche with a volume of 10’000 m^3 without snow entrainment does not reach the area of the railway station Eigergletscher.

In **scenario 2** an ice avalanche with a volume of 10’000 m^3 entrains around 50’000 m^3 of snow. The avalanche core flows past the railway station at a distance of 80 m (Fig. 4). However the powder cloud hits the railway station. The maximal impact pressure of the powder cloud is 10 kPa at the eastern end and decays rapidly to less than 1 kPa. The nearly 40 m high powder cloud only locally overflows the ridge of the Rotstock.

The simulation results of **scenario 3** when an icefall with a volume of 80’000 m^3 breaks off without snow entrainment are very similar to scenario 2. The core of the avalanche flows past the railway station at a distance of 20 m and the impact

Tab. 1: Overview of the investigated icefall scenarios

Scenario	*Ice volume*	*Entrainment volume*	*Suspension ratio*	*Average height of powder cloud*	*Zone of influence of core*	*Max. impact pressure powder cloud at railway station*
1	10’000 m^3	-	14%	22 m	300 m above railway station	<0.5 kPa
2	10’000 m^3	50’000 m^3	12%	37 m	80 m S of railway station	10 - 0.5 kPa
3	80’000 m^3	-	11%	32 m	20 m S of railway station	10 - 0.5 kPa
4	80’000 m^3	125’000 m^3	14%	53 m	Strikes the railway station	100 - 7 kPa

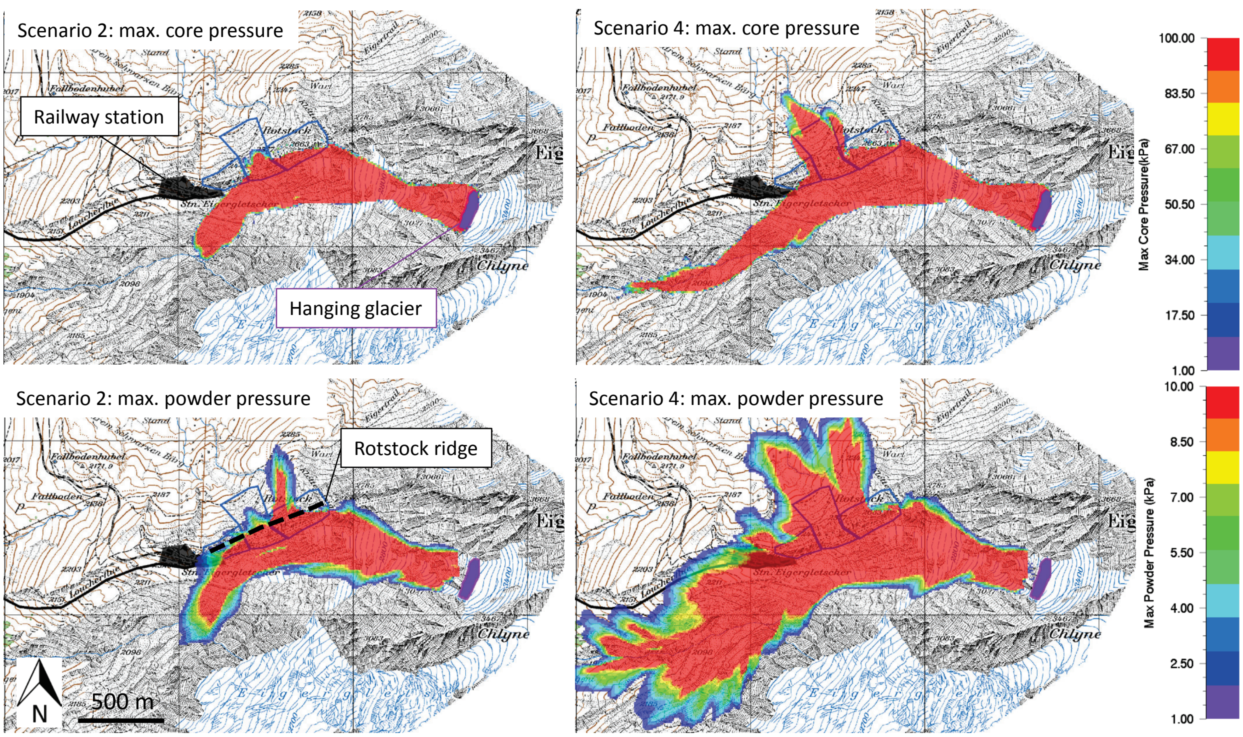

Fig. 4: Results of the RAMMS simulations for the scenarios 2 and 4. The top pictures show the maximal avalanche core pressure and the bottom pictures show the maximal powder pressure.

pressure of the powder cloud decays from 10 to 0.5 kPa in the area of the railway station. The ice avalanche reaches the area of the railway station 40 s after break off.

For the extreme **scenario 4** with an ice volume of 80’000 m³ and unstable snow conditions the railway station is heavily endangered by the core and powder cloud (Fig. 4). The ice avalanche entrains around 125’000 m^3 of snow. The calculated suspension ratio of the avalanche is nearly 15%. The mean height of the powder cloud is over 50 m. A part of the avalanche overflows the Rotstock ridge. The core of the avalanche strikes a small area of the railway station with an impact pressure of up to 100 kPa. Maximal impact pressures of the powder cloud greater than 50 kPa are possible. RAMMS probably calculates too high impact pressures of the powder cloud for scenario 4. The impact pressures were therefore adjusted, based on expert assumptions. The simulation results were an important base to develop the closure plans for the investigated scenarios.

5. CLOSURE PLANS

Based on the hazard assessment of the four scenarios we elaborated the closure plans A, B and C as part of the safety concept (see below and Fig. 5). On the plans four different zones with varying impact pressures are defined. The red zone is reached by the core of the avalanche with impact pressures of over 30 kPa. The dark blue zone is hit with impact pressures of the powder cloud varying between 5 and 10 kPa and in the light blue zone the impact pressure decreases from 5 to 2 kPa. In the blue zone a railway car can be overturned or doors and windows can break due to the impact pressure. In the yellow zone the impact pressure of the powder cloud decays from 2 to 0.5 kPa. We consider an impact pressure of 0.5 kPa as a lower limit for unprotected people.

Consequently, the necessary safety measures for all buildings, locations and infrastructures in the area of the railway station Eigergletscher were determined in relation to the different zones of the closure plans A, B and C. If for example closure plan B (Fig. 5) is operative, the railway station and a ski run are closed to the public and a specific type of railway wagons are used.

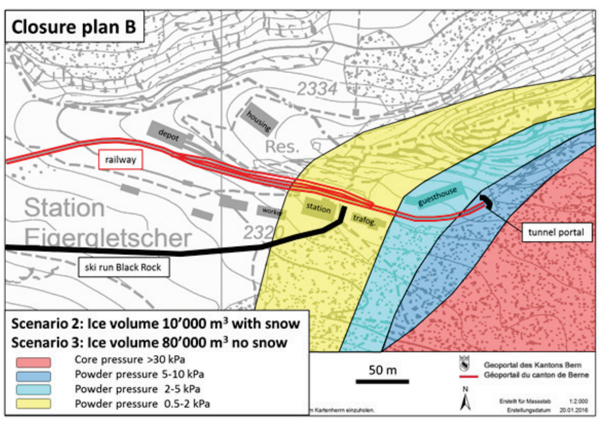

Fig. 5: Closure plan B with pressure zones for the area of the railway station Eigergletscher.

6. SAFETY MEASURES

The safety concept determines temporary safety measures for the different closure plans depending on the volume of an impending icefall from the hanging glacier in combination with the amount of erodible snow (Fig. 6). We recommended to install an early warning and alarm system as a basis for the safety concept (Sättele and Bründl, 2015), in order to detect an impending icefall in time and to minimize the closure times for the railway and ski area. An **early warning system** measures precursors of an event, in this case a local acceleration of the glacier surface velocity. In contrast, an **alarm system** detects the event itself in real time, i.e. the break-off of an ice lamella and the subsequent formation of an avalanche. A survey of the hanging glacier based on visual observations and interpretation of photos taken by an automatic camera were considered to be insufficient because neither the volume nor the timing of a break-off could be determined reliably, especially during bad visibility.

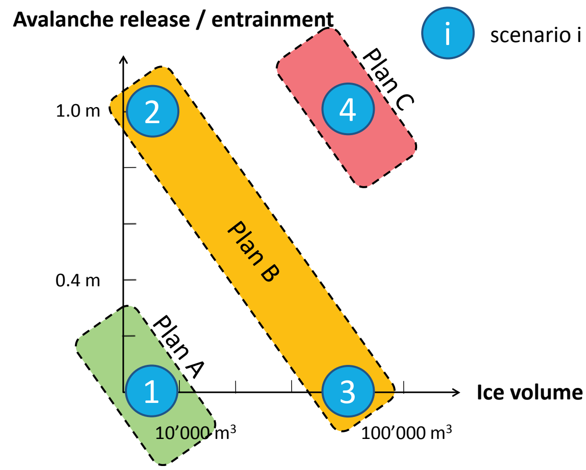

Fig. 6: Schematic diagram of the relation of the closure plans to the four investigated scenarios, which depend on the ice volume and the potential entrainment value.

A monitoring system consisting of a Ground-Based Interferometric Synthetic Aperture Radar and a Doppler radar, as well as several webcams was installed in February 2016 (Meier et al., 2016). The radars are located at the railway station, 1.8 km from the hanging glacier. The interferometric radar monitors the surface displacements of the glacier front continuously, independent of the weather conditions. This allows estimating the unstable ice volume and the surface velocities. The most promising approach to predict an icefall is based on the regular acceleration of the unstable ice volume prior to break-off (Pralong and Funk, 2006). The surface velocities are analysed manually every morning. If the surface velocity exceeds 0.15 m d^{-1} and if acceleration is observed a critical situation can develop. In practice a critical velocity of 0.4 m d^{-1} is often suggested to determine the time period of highly likely break-off occurrence (Faillettaz et al. 2016). The maximal surface velocity at the front of the hanging glacier on the Eiger W-face is generally below 0.05 m d^{-1} which is considered as non-critical. Additionally, the surface displacements on the glacier front are assessed to estimate the volume of an unstable ice lamella.

The stability of the snow cover and the amount of erodible snow is evaluated in winter by the safety service of the Jungfrau Railways. An erodible snow depth of 0.4 m is considered as the lower limit for which an ice avalanche can entrain relevant snow masses. If possible, avalanches are triggered artificially by helicopter blasting below the hanging glacier to reduce the amount of erodible snow. Based on this information and with the help of a decision tree (Fig. 7) the necessary safety measures and the closure plan to be applied are determined.

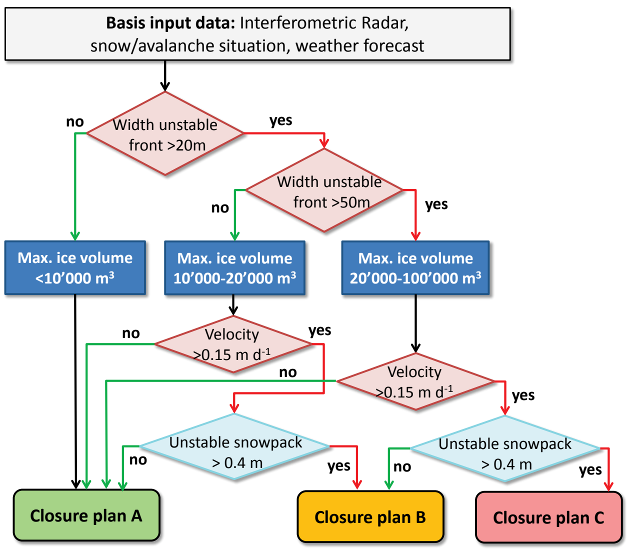

Fig. 7: Decision tree to determine the required closure plan in relation to the maximal ice volume, surface velocity and snowpack stability.

The Doppler radar detects releasing ice and/or snow avalanches around the clock and in all weather conditions and automatically triggers an alarm. The system sounds an alarm and stops the train if an avalanche of a certain minimum size is detected. Given a warning time of 35 to 45 s, both people and trains can move to safe places for example into the tunnel if they are in the danger zone when the avalanche is detected. The alarm system also allows a safe operation of the railway if closure plan B is activated. The Doppler radar is only operated in winter time.

In winter 2016 three icefalls were recognized one to a few days in advance by manually analysing the velocity time series. Shortly before failure the displacement velocities were larger than 0.4 m d^{-1} and the active area on the glacier front was smaller than 200 m^2 (Figs. 8 and 9). Because the ice volumes were smaller than 10'000 m^3 and the snow cover was sufficiently stable no closure plan had to be activated. The icefalls did not entrain much snow and the powder cloud caused negligible impact pressures in the area of the railway station. The icefalls were successfully detected with the Doppler radar system (Fig. 10) but because no closure plan was active, the alarm was suppressed.

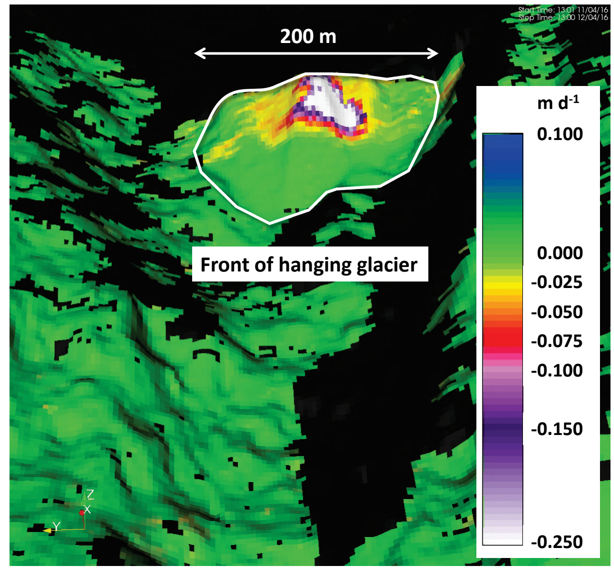

Fig. 8: Surface flow velocities (m d^{-1}) measured by the interferometric radar and projected onto a digital elevation model. On 12 April 2016 the velocities at the front of the hanging glacier were higher than 0.25 m d^{-1}. The front of the hanging glacier shown with the white line has a width of 200 m and the active area measures around 200 m^2.

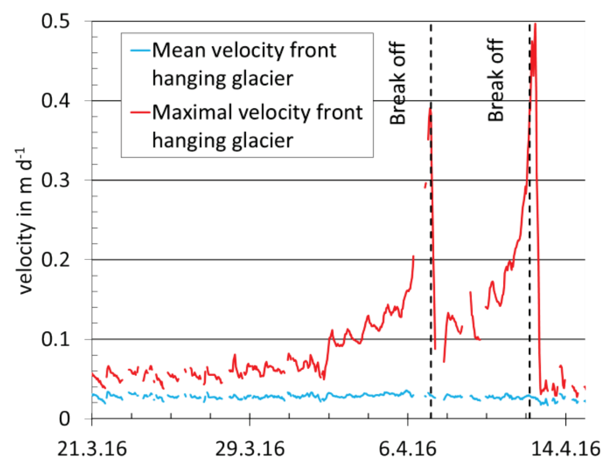

Fig. 9: Mean and maximal velocities at the front of the hanging glacier between 21 March 2016 and 14 April 2016 measured with the interferometric radar. A distinct increase in velocity prior to the two break-off events was observed.

A surprising number of 606 avalanches were detected between 24 February 2016 and 5 June 2016 in the area of the west face of the Eiger. Most avalanches were rather small and occurred after snowfall events or during warming periods. The avalanches usually stopped at the base of the rock faces in the potential trigger zone for secondary snow avalanches. This sluffing activity seems to disturb and stabilize the snowpack so that the probability of secondary avalanche releases is reduced.

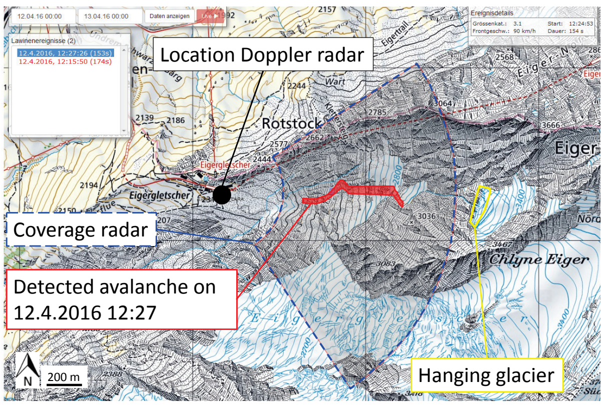

Fig. 10: GEOPRAEVENT online data portal with detected avalanche on 12 April 2016 and location of Doppler radar.

Finally, we proposed to elongate the lower end of the tunnel to the Jungfraujoch by a 45 m long snow shed so that the railway can no longer be hit by the core in scenario 4. Based on the RAMMS simulations we determined the avalanche actions on the planned snow shed.

7. CONCLUSIONS

The established safety concept that is based on closure maps and an early warning and alarm system allows a safe operation of the railway to the Jungfraujoch despite the imminent risk of ice avalanches. The installed interferometric radar has indicated several detachments of ice lamellas of the Eiger hanging glacier a couple of days in advance. A decision tree was developed to determine the required closure plan based on the interpretation of the radar signals and information on the snowpack stability. Thanks to the Doppler radar it is possible to keep the trains to the Jungfraujoch running safely, as the radar automatically detects larger avalanches and the trains can be stopped in safe places.

In this study we applied the research version of RAMMS, a two-layer numerical avalanche dynamics model, to analyse the hazard of ice avalanches breaking off the Eiger hanging glacier. RAMMS simulations were very helpful to quantify the differences between the four investigated scenarios and to establish detailed closure plans. The interaction of ice avalanches with the snowpack is particularly challenging and still poorly understood as there is a lack of good field data. The monitoring of ice avalanches with an interferometric and Doppler radar may contribute to a better understanding of this process.

In summary, we think that a safety concept including closure plans based on an avalanche dynamics study and on measurements with interferometric and Doppler radars can be considered as state-of-the-art technology for managing the risk of ice avalanches from hanging glaciers. This approach is particularly useful if there is relevant damage potential or if small ice volumes need to be detected because they may trigger secondary snow avalanches.

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