FIVE YEARS EXPERIENCE WITH AVALANCHE-, MUDFLOW- AND ROCKFALL- ALARM SYSTEMS IN SWITZERLAND

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ABSTRACT: Alarm systems detect avalanche flows, mud-flows or the opening of cracks in rock walls and automatically close roads and railway lines with traffic lights in case a dangerous event occurs. Eight new detecting systems have been built in Switzerland during the last five years using technology similar to that used in the Swiss avalanche and natural disaster warning system, IMIS, that consists now of more than 120 remote stations throughout the Swiss Alps. The alarm systems protect two narrow gauge railway lines and four access roads. To detect avalanche flow, three different types of sensors are used in combination: a medium range Doppler radar to detect avalanches already uphill from the detection station, force measurements in steel cables tied across the avalanche track equipped with vertical detecting cables reaching into the dense flow cross section, and geophones to measure vibrations in cables or seismic signals caused by avalanches. Crack openings are measured with special extensometers, mudflow, sediment- and boulder flow using a combined acoustic, force and vibration sensor. All systems are solar powered and radio controlled. Alarm conditions are transmitted as a specially coded short message from the detecting systems to the traffic light control systems. In several cases the traffic light systems are also solar powered. All systems are connected to control centres by radio - phone links. As well as the causes of alarms, system performance is continuously self checked and indicated at the control centres. These setups, based on Campbell loggers, guarantee very high reliability. So far the systems never failed to close traffic lines in cases of avalanches or mud-flows that blocked the road or track.

1. INTRODUCTION

Temporary protective measures have gained importance during the last decade. Improved knowledge of the process of avalanche formation, increased reliability of automatic remote measuring systems, new sensors, the possibility to measure close or even in potential release zones, and improved systems to support the assessment of actual danger all allow decreased closure times at a reduced level of residual risk for avalanche accidents in the zones to be protected (Gubler1989, 1992, 1996, 1998). The main condition for the application of temporary measures is the possibility, at any time, to close and evacuate even the extremes of the potentially endangered zone. Objects such as buildings, pylons etc. within the endangered zone have to be designed to withstand avalanche forces. Alarm systems that detect movements of avalanches and close the endangered section of a road or railway line in time to allow vehicles to leave the endangered zone before the avalanche reaches the traffic line are especially suited to protecting local roads with low to intermediate traffic volumes, or slow-moving mountain trains that typically have very short breaking distances.

This article defines typical conditions for alarm systems, estimates residual risk and cost efficiency, describes typical systems operational in Switzerland and summarizes the experience of the combined 28 years of operating time of the seven systems built during the last six years.

2. PURPOSE AND BASIC DESIGN OF ALARM SYSTEMS

An alarm system has to automatically close and evacuate an endangered zone to be protected in case of the detection of a dangerous situation. Danger is defined as the probability of occurrence of debris from an avalanche, mudflow, rockfall or debris-flow within the zone to be protected. The pre-warning time (time period between alarm and the arrival of first debris) has to allow vehicles and humans to reach safe locations, or to leave the endangered zone, or to stop outside.

Basic alarm systems consist of at least three modules: the detecting system, the signalling system and the control system (Fig.1). The detecting system has to detect a dangerous

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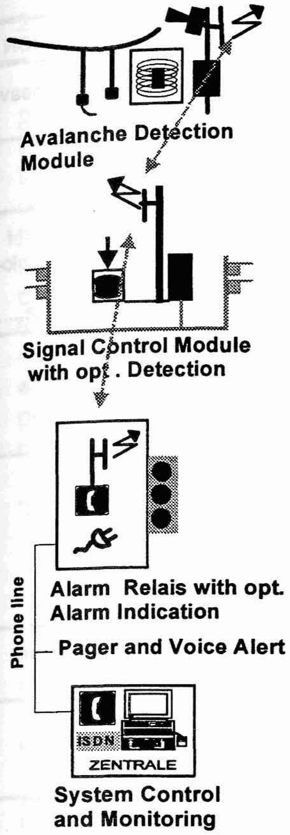


Figure 1: Basic setup of an alarm system.

movement. The signalling system alarms endangered persons in time audiovisually with lights, sirens, barriers etc. The control system, in most cases integrated in a control- or maintenance centre, monitors the operational states of the detecting and the signalling systems, allows manually setting and resetting alarms, and updating alarm conditions. Detecting and signalling systems are connected by a radio link. Quite often the signalling system is connected to the public phone and serves as a relay between the radio link and the phone line that connects to the control- and maintenance centre. In some cases the signalling site is also very remote without access to phone and power. In these cases the systems at the traffic line are also battery/solar powered and linked by a further radio link to a radio - phone relay at a less remote site.

2.1. *Detecting system*

Detecting systems have to measure movements and flows close to their origin to guaranty enough pre-warning time. Basically long range and short range detectors could fulfill this requirement. In practice long range systems, e.g. gated Doppler radars, optical, seismic or acoustical systems are less redundant (only one type of sensor), depend on weather conditions (optical systems), do not discriminate environmental noise from the true event (long range seismic) or may detect a flow too late (infrasonic and seismic systems) or are very expensive (gated long range radar). Therefore most alarm systems built worldwide are of the short range type, where the endangering event is detected with multiple sensors close or at its origin. Detectors have to function in a harsh alpine environment at remote locations inaccessible for long periods of time and have to be powered by batteries and solar cells. The types of sensors depend on the processes to be measured: flows or fast movements (avalanches, mud-flows), slow dislocations (initiation process for rockfall), forces (interaction with flows), noise (sediment enriched torrent flows), and seismic signals. The sensors in use are summarised in table 1. The detecting system analyses the quasi-continuous recordings of appropriate sensors and determines the actual level of danger with respect to the zone to be protected. If a predefined level of danger is reached, an alarm is sent to the signalling system. The system often continues to measure, at increased time resolution, during the ongoing event and analyses data online. A short period (1 to 2min) after the alarm transmission, a digital status report is sent to the control- and maintenance centre. In some cases additional detecting systems are installed at the traffic line to detect a flow or debris. In such cases, if no interaction is detected within a given time interval after the alarm, the alarm may be reset automatically. Data and signal status are also sent to the control centre, where the alarm can be reset manually if necessary. In most cases the detecting system will provide information on the magnitude of the event, proposing a false alarm if it turned out that the event was not likely to reach the traffic line. If high speed snow avalanches have to be detected, the available pre-warning time is small (typically 30 to 45sec.), therefore the alarm has to be transmitted quickly within the first one to five sec. after the first detection of the flow. Continuing measurements may reveal that the avalanche mass or flow length was too small to reach the traffic line. This is the reason for the delayed report to the control centre. Mud-flows move slower and allow for longer measurement periods. Also measurements of the opening speed of crevasses in rocks as precursors for large rock falls allow for larger pre-warning times.

The detecting system has to be ready again to detect the next alarming situation before the potentially endangered zone is reopened. Therefore, the dead time for the automatic system reset is less than 10 minutes for most systems. The systems perform periodic self-tests. All relevant system parameters are automatically reported to the control centre.

The detecting systems are built around a Campbell CR10X Logger. These are the main building blocks: solar power system with 130Ah of backup battery fed by two solar panels of

CRITERIA	PARAMETER	TRIGGER	RECOGNITION	CONDITIONS	DISTORTION
CABLE FORCES	dynamic and static tension	dense and powder avalanche	RMS of dynamic force, signal duration	channelled flow	wind with heavy riming
CABLE VIBRATION	vibration speed	dense and powder avalanche	RMS of vibration, signal duration	channelled flow	wind
GROUND MOTION	ground motion speed	dense and powder avalanche, mud-flow	RMS of motion and signal duration, signature in frequ. domain	increased interaction of flow with ground	many kinds of sources: explosions, traffic, earth quake.....
DOPPLER RADAR	speed and reflectivity of flow	dense and powder avalanche, mud-flow	speed, reflectivity, flow direction	observation in parallel to flow direction. No other moving parts as trees in the wind	instrument riming, trees
COMBINED SENSOR	pressure, weight of debris, ground motion speed, noise from sediments	dense and powder avalanche, mud-flow, torrent flow	RMS of AC-signals, DC-signal of force	Flows overflow road or track, sensor at uphill border	traffic noise
EXTENSOMETER	crack width	increase of opening speed	speed	relative movement of nearby rock masses	local rockfall
PRESSURES, FORCES	dynamic force	dense avalanche	RMS of force	pressure plates on natural or artificial obstacles in track	rockfall
PULL WIRES	electrical resistance	starting rockfall	fracture of wire	relative movement of nearby rock masses	local rockfall

Table 1: Most important sensors of detecting systems. RMS: root mean square value of alternating (AC) signal.

55W each. Data transmission is based on Motorola radios and RF95 modems from Campbell (CSI) with special programming that allows transmitting alarms very quickly to the receiving site without a logger involved. Interfaces for different types of sensors as Doppler radars, geophones, strain gauges, extensometers etc. connect the sensors to the logger. These interfaces include lightning protection, gain control, sensitivity control, signal integration, RMS detection, counters, power control for the sensors and are connected to the logger via SDM counter modules, D/A converters, analog inputs and excitation outputs. The logger with its control software performs the measurements, the power management, controls data transmission, stores data, performs self tests, analyses data and initializes alarms. The critical level for an alarming situation can be defined in many ways: minimal duration of continuous processes, threshold values for forces, vibration amplitudes (using RMS values), speed measured by microwave Doppler radar, reflected signal power by the moving avalanche. The different threshold conditions can be logically combined. This logic allows a rough estimate of the magnitude of the avalanche, an important parameter for the actual danger at the road or track site.

2.2 *Signalling system*

The signalling system consists of several modules: the power module with back-up batteries, the transmission- and relay module, the signal control and test module for traffic lights and sirens etc. and optional sensor interfaces for local flow- and debris detection. In its simplest configuration the RF-modem of the transmission module provides the alarm signal directly to a commercial traffic light system. In a standard system, the control of the lights and sirens uses a CR10X with some additional hardware. This system uses much less power than a standard commercial system, allows for automatic lamp tests, and for setting and resetting signals from the control centre.

2.3 Control module

The purpose of the control module is to periodically interrogate the remote systems and to display the operating status of these systems, to alarm maintenance crews in case of closures of the traffic line or system failures, to provide the possibility to set /reset signals manually and to display data from the sensors. This is basically a software running on a PC (NT op. system) connected to the public phone by a modem. The setup allows the system provider to do checks and maintenance from almost any point in the world. Systems are only sold with mandatory maintenance contracts.

3. TYPICAL SYSTEMS

So far four systems have been installed to protect roads and two systems to protect rack- railway lines from avalanches, one system to protect a road from a mud flow starting from the steep front slope of a permafrost area, and one system to protect traffic on a road section from a large rockfall.

3.1 Typical avalanche endangering a road

The Linterngraben avalanche endangers the access road to Adelboden, a tourist village in the Berner Oberland. Several investigations are necessary for a correct design of an alarm system, including determination of the extreme borders of the endangered zone, safe locations within this zone that could be used by pedestrians, as well as safe locations to stop the traffic. A safety check for the maximum potential stopping area must assure that stopped cars are not endangered by other nearby avalanches. Investigations include the dynamics of the avalanches with respect to the speed of powder, dense and wet snow avalanches along the track, flow heights and speeds at possible locations for detecting systems, and cross sections of the track. Save positions for detecting systems in the upper part of the track must be located. For the risk analyses mean and maximum traffic volume on the road, percent of busses, number of persons per car, portion of cars that use the road section daily, traffic speed under realistic weather and road conditions have to be known. With this information residual risk for individuals and institutions (road authorities, railway companies) including aversion factors, can be determined and the risk reduction and cost efficiency of the safety measures can be estimated. An alarm system should only be built if risk reduction is larger than 0.005 fatalities per year, the investment is reasonable, and cost efficiency is below 8 billion Sfr per prevented fatality. Careful analyses may reveal that other measures or investments to other avalanche tracks would be more cost efficient.

For the Lintergraben avalanche we found the following results: the mean return period T for the avalanche hitting the road is 5y. Typical speed of a channelled avalanche with a return period of 80y is 35 - 40m/s. Flow width at the road is 30 - 40m with a flow height of up to 8m. The development of a large powder snow avalanche is likely but does not directly endanger the road. For the available pre-warning time for the highest possible location for a detecting system we get 38s. The minimal necessary pre-warning time defined by the length of the endangered road section is 24s.

Mean/ maximum number of cars per day, DTV, is 3000/7000. Up to 1% of the vehicles are busses. The number of passengers per car β is 1.8/ 2.4. The probability of death PA is estimated to be 0.18. The lengths of the endangered road section including the breaking distance, s, amounts to 80m. Traffic speed v is assumed as 40km/h. Using these numbers in eq. 1, we get an institutional risk, R, of 0.016/0.043 fatalities per year and an individual risk for somebody using the road twice daily $r=2.7\cdot 10^{-6}y^{-1}$.

$$R = \frac{s \cdot DTV}{v \cdot 24h} \beta \cdot Pa \qquad (1)$$

Investment and maintenance costs for a typical life time of alarm system of n=15y add up to I_0 = 0.25 billion Sfr. With the assumption that the alarm system correctly detects and signals 95% of the avalanches that hit the road, the system provides a risk reduction, R_v, of 0.015 fatalities per year resulting in a cost efficiency KE of 1.1 billion Sfr per prevented fatality.

$$KE = \frac{I0}{Rv \cdot n} \qquad (2)$$

The remaining residual institutional risk including an appropriate aversion factor is still significantly larger than 10^{-3} fatalities per year which is still fairly high especially if one takes into account that there is a second comparable avalanche that endangers the road.

3.2 *Typical alarm systems*

The detecting system at the Lintergraben is located some 100m below the lower boundary of the release zone, at only 1650m.a.s.l. The road is at 970m.a.s.l. Track length from detection to road is 1500m. At the location of detection the avalanche runs in a channel approximately 160m wide and 50m deep. The pylon with the electronic boxes, solar system, Doppler radar and radio antenna is on the right rim of the channel. The pylon is fixed in a standard way on three micro-piles. The 15mm steel cable that crosses the channel is fixed to the footplate of the pylon and holds 150kN (Fig.2). An additional pile at an angle of roughly 45° off vertical takes off the strain from the cable from the standard foundation. On the opposite side of the channel the cable is anchored by a 4.5m cable anchor in the ground. There are four vertical detecting cables hanging from the horizontal cable. Each cable reaches about 1 to 2m above ground and supports a 15kg concrete block attached to its end. Avalanches running in the channel pull on these cables and cause high tensions in the horizontal supporting cable. These forces are measured with a strain gauge force sensor integrated in the supporting cable close to the pylon. A geophone mounted to the cable measures oscillations caused by avalanches (Fig.3). The Doppler radar with a range of up to 500m points toward the beginning of the channel, just below the release zone. In other installations reenforced pylons are mounted on avalanche splitters and special sheltering for the electronics had to be constructed (Fig. 3). For the Lintergraben system data and alarms are transmitted by radio down to the signalling

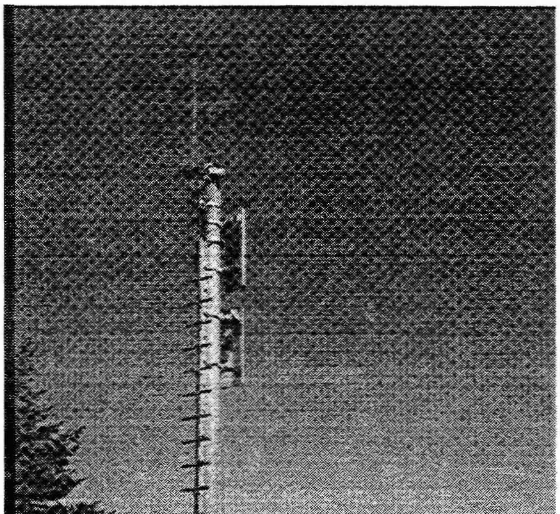


Figure 2: Typical pylon with Doppler radar, solar cells, antenna, electronic boxes and steel cable with integrated sensors.

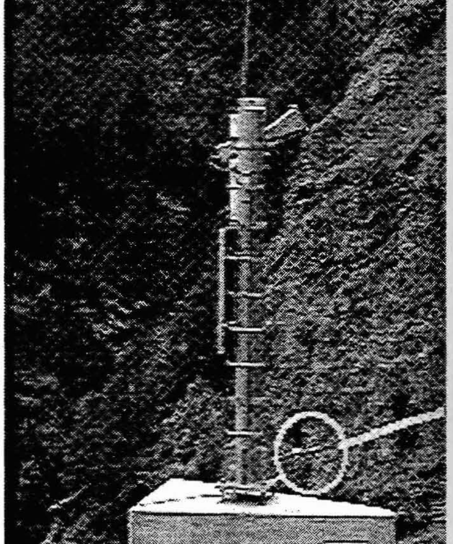


Figure 3: Special pylon on an avalanche splitter. Cable with integrated sensors leading to the right.

system at the road. The control module is installed at the regional maintenance centre some 10km from the avalanche.

The two systems built to protect railway lines both have two separate detecting systems located on two mayor branches of the avalanche track. Both detecting systems report to the same signalling system. In one case the alarm signal is fed directly to the railway signalling and safety system, in the other case it turned out to be more cost efficient to build a solar powered signalling system at the track combined with sensors detecting mudflow and avalanche debris at the track. This signalling system is connected by radio to the nearest railway station where audiovisual, phone and pager alarms are installed. The control module is installed in the main maintenance centre of the railway company some 50km from the avalanche. From this centre the signals can be set and reset manually too. The special mudflow and avalanche debris sensor mentioned above combines a pressure measurement plate (diameter 0.5m, 200kPa) with a shock measurement (geophone) and a sediment flow measuring system that records the high frequency sound originating from sediments and gravel suspended in a torrent flow or mud flow hitting the detector plate.

Close to Innertkirchen at the Grimselpass the road is endangered by a huge rockfall. Two almost vertical rock plates of 250,000m^3 and 25,000m^3 move slowly outward at their top with speeds of up to several mm per day. Geologists forecast a mayor rockfall within a few month. Two independent detecting systems measure the opening of the cracks with specially constructed extensometers (Fig.4). Additional wires across the cracks will be torn apart if fast movement starts. The alarms (if opening speed reaches a critical level or if wires break) are sent directly to two independent, solar powered traffic lights on both sites of the endangered road section and together with data to the control centre of a nearby power plant. A geologist in Bern, responsible for the assessment of actual danger, gets daily data directly from the two detecting sites. As for the systems mentioned above, the signalling systems perform periodic lamp tests and system self tests. The results are transmitted to the control centre. In case of a failure or an alarm an audiovisual alarm alerts the control crew.

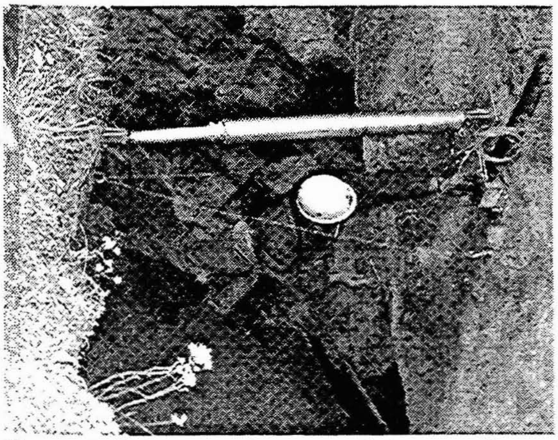
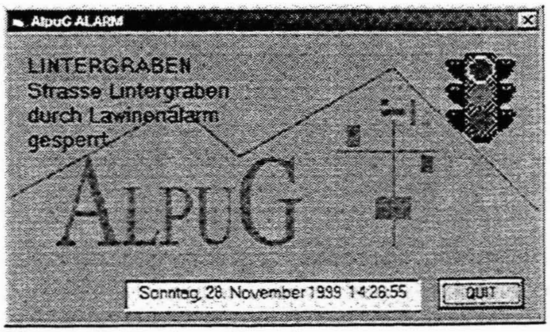


Figure 4: Extensometers, special sensor to measure relative movement of rock masses with high resolution.

On September 4,2000 during a heavy rainfall speeds suddenly increased within a few minutes from 0.12mm/hour to more than 10mm/hour and a few thousand m^3 of rock broke off. Some blocks just reached the border of the road and destroyed some of the protecting nets. The alarm system correctly closed the road within the first few seconds of the increase of dislocation speed and alarmed the maintenance and control centre. After this first rockfall the speeds decreased again and the road was reopened a week later.

4. DATA AND EXPERIENCE

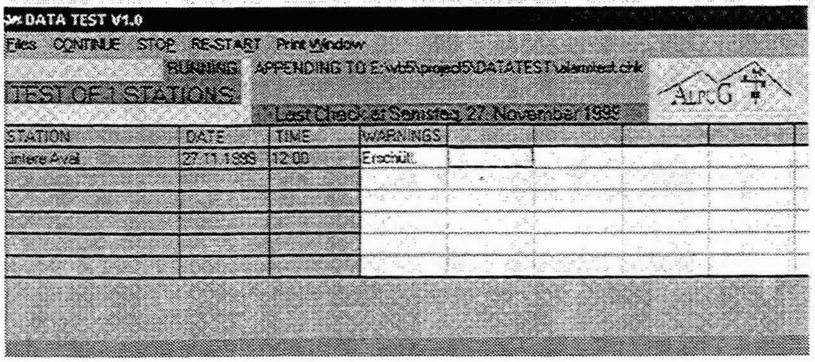
The 10 detecting systems operational so far have a combined operating time of 28 years. Installed are 7 Doppler modules built by AlpuG (range 500m, X-band, antenna gain 20dB), 7 cable force systems, 7 cable vibration systems, two 3-m extensometer, one combined debris- and sediment sensor and two geophones to detect mud flows. The alarms are fed to two commercial traffic light systems, three solar powered signalling systems and to one railway control system. The detecting and



LINTERGRABEN
Strasse Lintergraben
durch Lawinenalarm
gesperrt

Sonntag, 28. November 1999 14:26:55

Figure 5: Display of an alarm



DATA TEST V1.0

RUNNING APPENDING TO E:\vb5\projed5\DATATEST\alarmtest.chk

TEST OF 1 STATIONS

Last Check at Sonntag 27 November 1999

STATION	DATE	TIME	WARNINGS
Lintere Aval	27.11.1999	12:00	Erschüt.

Figure 6: Typical status display for remote stations.

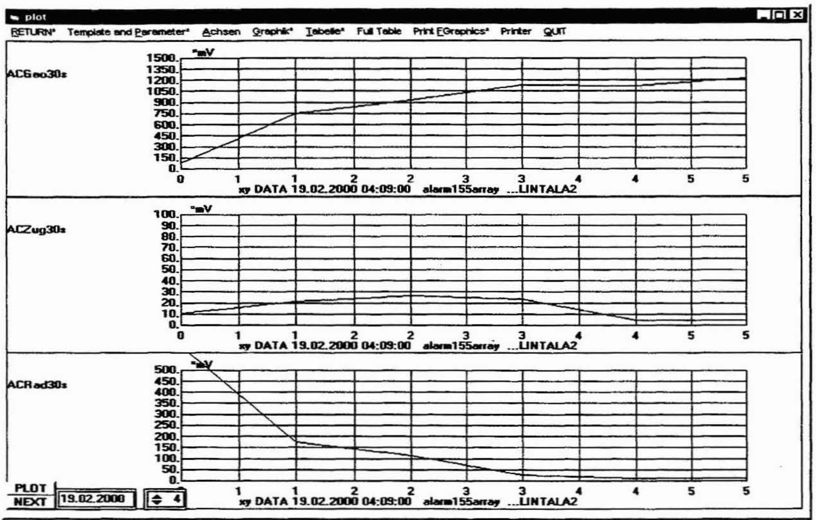


Figure 7: Signals from a small to medium avalanche.up-down: RMS Geophone, RMS cable force, RMS reflected power Doppler radar. Full time scale 30s.

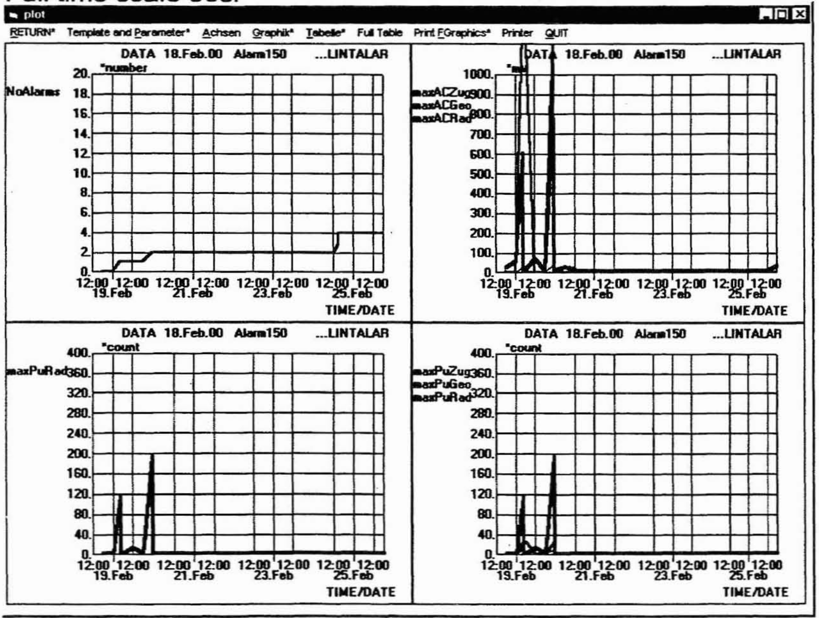


Figure 8: No of alarms, max. speed of avalanche (7p/ms^{-1}), max.RMS-values, max. pulse/s.

signalling modules are operationally controlled by four control modules in control- and maintenance centres.

4.1 *Typical data*

There are two types of data acquired by the control centres from the remote modules: control data and alarm data. The transmission of alarm data is initiated by the remote modules, and control data are acquired periodically by the control module. The transmission of alarms to the control module immediately sets off an audiovisual alarm (Fig.5). Each data record contains a status number that defines the actual operating condition of the remote module. In addition incoming data are scanned by special software that allows for range checks of critical parameters. Alarms and problems are indicated in a table (Fig.6) on the display of the control PC and are written to a protocol file. All parameters can be graphed and displayed in tables.

The alarm data contain special records with increased time resolution of seismograms, Doppler radar signals, dislocation measurements etc (Fig.7). The control data include battery voltage, temperatures, all sensor outputs, state of local switches, excitation voltages, status and elaborated parameters as e. g. maximum measured avalanche speed. From these data flow speed and flow duration at the detecting location can be deduced (Fig.8). These are important data for the adjustments of the alarm parameters and to get information of the actual state of the track. The state of the track determines how far an avalanche of a given size may

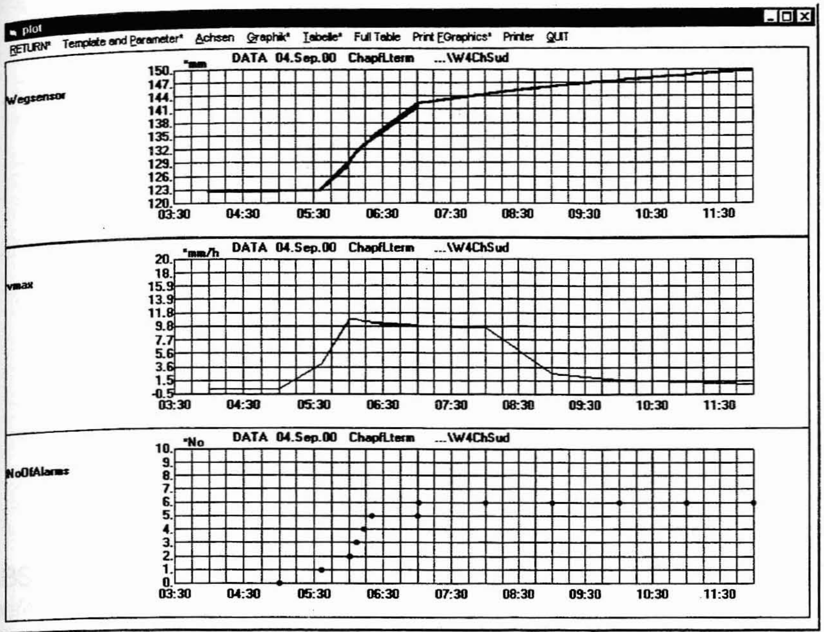


Figure 9: Data from the rockfall alarm: extensometer, max. speed and alarms. The traffic lights were set automatically at 05h35 and the rockfall occurred about 10 min later. Pre-trigger and past-trigger data at a time resolution of 5s were stored too.

run. As part of the maintenance contract AlpuG evaluates each alarm and gives advices to local safety managers.

4.2 *Alarms - false alarms - missed alarms*

So far the systems registered about 30 alarms. For three of the five avalanche alarm systems 50 to 66% of the avalanches came very close to the traffic line or blocked it. For the other two systems with very long tracks leading to very low elevations the percentage of false alarms is higher. So far these avalanches never reached close to the traffic lines. For these cases the return period of winters with avalanches blocking the road or railway track are much larger (10 to 30y). The rockfall alarm system correctly detected an upcoming rockfall and the mudflow detecting systems closed the endangered road several times.

The alarm systems missed so far one avalanche, a small spring-type wet avalanche that started within old deposits in the channel below the detecting system and reached the road.

The number of false alarms can be reduced for these systems in two ways: 1. the critical thresholds can be increased, if the effective pre-warning time 'is larger than the minimum necessary pre-warning time, the measuring period can be increased by several seconds to discriminate smaller avalanches, 2. the signalling system can be deactivated from the control centre if snow and track conditions definitely do not allow avalanches to reach the traffic line though there may be some avalanche activity 1500 to 2000m higher up. All relevant system parameters can be remotely controlled, therefore adaptations are possible any time. Because the systems are safety relevant, we do these changes only in small steps, starting with low threshold values.

So far we had to minor system failures. In one case a Doppler radar malfunctioned as a result of water entering into the system, and in the second case a direct lightning stroke hit a pylon and partly affected an excitation output of the logger. In both cases, because of the self tests and the high system redundance the errors were indicated immediately and the systems still worked ok with the affected sensors turned off from the maintenance centre.

5. CONCLUSIONS

Alarm systems based on recent logger and sensor technology as well as improved knowledge in avalanche formation and avalanche dynamics have proved to be cost effective if some important conditions are fulfilled. The main condition is that it has to be possible to close and evacuate the endangered zone any time and within a very short period of only a few tens of seconds.

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