Design of a Measurement Assembly to Study In Situ Rock Damage Driven by Freezing

Samuel Weber, Stephan Gruber, Lucas Girard
Glaciology, Geomorphodynamics, Geochronology; Geography Department, University of Zurich, Switzerland

Jan Beutel
Computer Engineering and Networks Laboratory, ETH Zurich, Switzerland

Abstract

We describe the design of an acoustic emission (AE) measurement assembly for reliable acquisition of a multi-year time-series in steep alpine rock-walls. The motivation for collection of these data is to enhance understanding of freezing-induced rock damage. Because measurements in natural rock slopes are challenging, this study investigates technical options suitable to capture AE signals from differing depths while incurring minimal signal loss between the rock and the sensor. We first outline the requirements for the measurement assembly and present two generic solutions to be evaluated and refined. We then present candidate materials for building components of the assembly and experimentally estimate their attenuation coefficients and signal loss at the rock-sensor contact. Based on these results, we present the final design chosen for the measurement assembly and briefly report initial experiences from a field deployment site at 3500 m a.s.l. at Jungfraujoch, Switzerland.

Keywords: acoustic emission; measurement assembly; depth; mountain permafrost; rock fracturing; microgelivation.

Introduction

In cold regions, ice formation is known to be an important driver of rock fracturing (Matsuoka & Murton 2008) and is commonly referred to as frost weathering. The formation of ice in rock induces pressure variations in rock pores and cracks, which can cause damage near the surface as well as at a depth of up to several meters (Murton et al. 2006). This process may be crucial for the slow preconditioning of rock fall from warming permafrost areas (Gruber & Haeberli 2007). Most knowledge about the associated processes stems from theoretical studies (Walder & Hallet 1985) or laboratory experiments (Murton et al. 2006). However, the transfer of corresponding insights to natural conditions, involving strong spatial and temporal heterogeneity is nontrivial.

The monitoring of acoustic emissions (AE) is a powerful technique to track the evolution of damage. AE signals are transient elastic waves generated by the release of energy during rapid local changes of inelastic strains in solid materials. These events are accompanied by damage increase, extension, or shearing of existing fractures (Scholz 1968). AE monitoring has been used at the rock sample scale (Lockner 1993) in laboratory studies and under natural conditions to monitor seismicity and rock bursts in mines and tunnels as well as slope instabilities (Amitrano et al. 2005). In a four-day experiment, Amitrano et al. (2011) used AE monitoring to investigate freezing-induced rock damage in a high-elevation rock slope. AE activity was observed to be more intense during freezing periods and in locations subject to diurnal flow of melt water from snow patches.

To better understand rock damage under natural conditions, continuous AE monitoring and the ability to estimate source depths of events are desirable. We expect the investigation of diurnal and seasonal cycles, as well as rock in an advanced stage of pre-fracturing, to be important for the robust scaling of theoretical insight to field conditions. In this paper, we describe the design of an AE measurement assembly for reliable acquisition of a multi-year time-series in steep alpine rock-walls relying on commercial sensors. Because long-term measurements in natural rock slopes are challenging, this study investigates technical options suitable to capture AE signals from differing depths while incurring minimal signal loss between the rock and the sensor.

We first outline the requirements for the measurement assembly, present two generic solutions that are evaluated and refined and, based on this, identify the problems to be addressed in detail. We then present candidate materials for building parts of the assembly and experimentally estimate their attenuation coefficients and the signal loss at the rock-sensor contact. Based on these results, we present the final design chosen for the measurement assembly and briefly report first experiences from a field deployment site at 3500 m a.s.l. at Jungfraujoch, Switzerland.

Requirements and Problem Statement

In this section, we first present the type of acoustic transducer used in this study and then detail the requirement of the measurement assembly to be designed. By measurement assembly, we refer to the technique used to transmit acoustic signals from a given depth of the rock-wall to an acoustic transducer.

Acoustic signals can be generated by the activation of small flaws such as shearing of a millimeter-long crack, as well as by larger mass movements such as rock falls. In this study, our goal is to monitor the acoustic signals generated by ‘small events.’ There are two reasons for this. First, smaller events are statistically more likely to occur, which allows us to obtain large catalogs of events and perform robust statistical analysis. Secondly, our goal is to understand the mechanisms that progressively damage rock and pre-condition rock falls. In other words, we are interested in the precursors of rock falls. Therefore, we have chosen to use piezoelectric transducers (R6alpha, Physical Acoustics Limited, UK) that can capture acoustic signals in the frequency range 1–150 kHz. The typical size of the flaws (i.e., defects, cracks, etc.) that are likely to generate AE in this frequency range is on the order of millimeters. Within this frequency range, events where the source is located up to about a meter from the transducer can be detected, while events generated at larger distances are attenuated. We hereafter refer to the acoustic transducers as AE sensors.

The assembly to be designed will enable a reliable, consistent, and repeatable measurement. At the scale of one meter, variations in temperature and ice-induced stress are expected to dominantly occur along the dimension of depth, oriented normal to the rock surface. The use of two sensors, installed at differing depths, could provide a *zonation* of the source depths. While installing more than two sensors may provide more accurate localization, it considerably complicates the installation, increases the disturbance of the rock mass investigated, and increases the cost of a single setup.

Measuring at depth requires a borehole. Two methods are then considered for capturing the AE signal: (1) insertion of the sensor into the borehole, or (2) insertion of a waveguide for transmitting the signal to the rock surface where the sensor is installed. Water flow in the borehole can alter moisture conditions at depth and thus cause spurious AE events related to freezing/thawing (Kaufmann 1999). To avoid such events, the borehole must be sealed after installation. To enable long-term measurements, the ability to exchange sensors in the borehole is desired. Based on these requirements, we propose two generic designs for the measurement assembly to be tested and refined (Fig. 1):

(1) The construction of a **casing**, which accommodates the sensor within the borehole. The rock-sensor contact is made using a thin plate glued to the bottom of the borehole. While the AE signal transmission should be good for this conductive plate, other parts of the casing should exhibit strong attenuation to avoid pollution by acoustic events originating from different depths. The casing has to be made waterproof and extend to the rock surface, where a lid allows signal extraction as well as sensor exchange.

(2) A **waveguide**-based solution uses a thin rod fixed to the bottom of a borehole and a sensor installed on top above the rock surface. The sensor requires mechanical protection to prevent damage from rock fall or icing.

We investigate the feasibility of both solutions, and evaluate their impact on the measured AE signal.

Background

As a basis for investigating suitable materials, we briefly review the propagation of elastic waves in solids, for simplicity only considering compression waves (P-waves). Assuming a homogeneous, isotropic medium, the compressional velocity of elastic waves is given by (e.g., Hardy 2003):

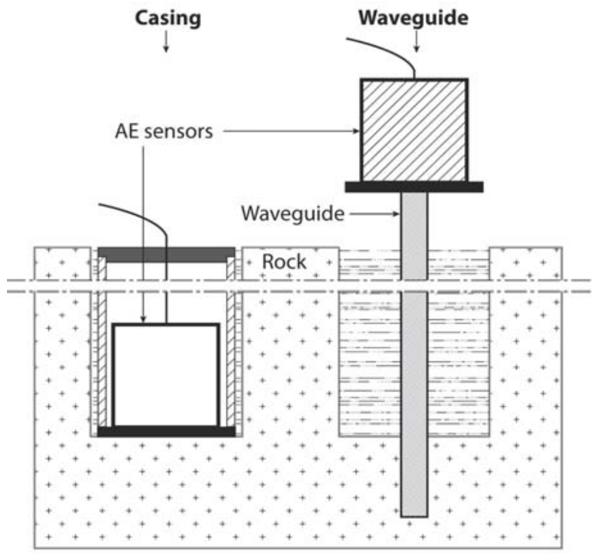

Figure. 1. The two generic measurement assemblies: Casing and waveguide.

$$C = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+2\nu)(1+\nu)}} \quad (1)$$

where ρ is the density, E the Young modulus, and ν the Poisson ratio. The acoustic impedance related to P-waves can then be defined as:

$$Z = \rho C \quad (2)$$

The transmission coefficient between two different materials with acoustic impedances Z_a and Z_b can then be calculated as:

$$T = 1 - \left((Z_a - Z_b)/(Z_a + Z_b)\right)^2 \quad (3)$$

The largest transmission of the elastic wave therefore occurs between materials that have similar acoustic impedances. Another property that needs to be accounted for in the choice of the materials is the attenuation coefficient. As an elastic wave propagates from a source through a medium, amplitude decrease due to absorption can be estimated as:

$$A^l = A_0^l e^{-\alpha r} \quad (4)$$

where A^l_0 is the linear amplitude at the source, A^l that at a distance r from the source, and α is the frequency-dependent attenuation coefficient.

Candidate Materials and Their Evaluation

Candidate materials for the measurement assembly

Two categories of materials are needed for the assembly: transmitting and attenuating materials. The transmitting

Table 1. Material properties.

Material	Density (kg/m^3)	Young modulus (GPa)	Poisson's ratio	Speed of sound C (m/s)	Acoustic impedance Z (SI)	Transmission coefficient T	Attenuation coefficient α (dB/m)
Mild steel	7900	200	0.3	5838	46.1 10^6	0.71	30
Aluminum	2700	70	0.35	6451	17.4 10^6	0.99	10
Chromium steel	7900	200	0.3	5838	46.1 10^6	0.71	60
POM C	1420	3	0.35	1841	2.61 10^6	0.53	71
Geo-Gel	1020	0.1	0.45	610	0.62 10^6	0.16	151
Gneiss	2700	56	0.28	5149	13.9 10^6	1	35

materials should have a low impedance mismatch with the rock (i.e., large transmission coefficient) and a small attenuation coefficient, while the damping materials should have the opposite properties: low transmission coefficient and large attenuation.

As transmitting candidate materials we considered ordinary mild steel, chromium steel, and aluminum because metals are typically good acoustic transmitters. For the damping material, we selected a thermoplastic polymer called POM-C (DuPont Delrin). We also examined the physical properties of a two-component polyurethane-resin (Geo-Gel from Kuempel AG, Sarnen, Switzerland). This is a slow-hardening resin with a viscosity of 850 mPa·s (i.e., between olive oil and liquid honey). It could thus be injected in the borehole after the installation of the measurement assembly in order to seal the hole. Finally, the properties of gneiss (from Ticino, Switzerland) were considered as representative of those of the rock at the planned field site.

Table 1 reports the mechanical properties of these materials. The speed of sound, acoustic impedance, and transmission coefficient within gneiss were calculated as detailed above. Considering these results, aluminum appears as the best candidate material to build the rock-sensor contact. In the 'casing-based-solution' this contact is made through a thin metal plate, while in the 'waveguide-based-solution' the contact is made through the waveguide itself. The results also suggest that POM-C is suitable for building the casing since it has a low transmission coefficient with gneiss. Similarly, the Geo-Gel has a low transmission coefficient when applied to gneiss. Its use as a sealing agent would thus provide further reflection and attenuation of spurious AE signals.

Experimental determination of the attenuation coefficient

To facilitate comparison, the attenuation coefficients of candidate materials were determined experimentally (Fig. 2). This was achieved using two AE sensors with a given spacing placed on a sample of each material. An artificial source was applied, and the amplitude of the resulting stress wave monitored with both AE sensors. The source was either a FieldCal pulser (Physical Acoustics Limited, UK) or the breaking of 0.5-mm pencil lead. The frequency of the FieldCal was set to 60 kHz, the resonant frequency of the AE sensors used. The AE sensors and the FieldCal were coupled to the

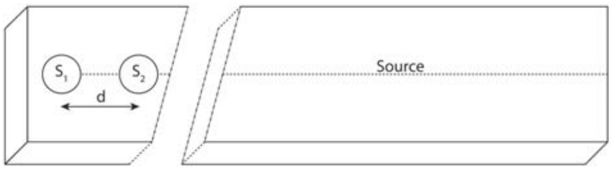

Figure 2. Experimental set-up for determination of the attenuation coefficient.

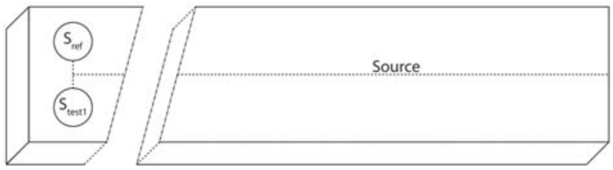

Figure 3. Experimental set-up for determination of attenuation of the rock-sensor contact.

rock using an ultrasonic coupling gel (UCA2 from Sofranel, France). The attenuation coefficient, as defined by equation 4, can then be calculated as $\alpha = \Delta A/d$, where ΔA is the measured amplitude difference (in dB) between the AE sensors separated by distance d. The results, reported in Table 1, suggest that mild steel and aluminum have lower attenuation coefficients than chromium steel. Damping materials indeed demonstrated higher attenuation coefficients, with that of Geo-Gel being about one order of magnitude greater than that of the metals.

Attenuation of the rock-sensor contact

Signal loss at the rock-sensor contact was determined experimentally (Fig. 3) for the two possible solutions. Experiments were performed on a rectangular gneiss block (15 cm x 10 cm x 70 cm) using an artificial source and two receiving AE sensors (using ultrasonic coupling gel): a reference sensor, directly coupled to the rock, and a test 'rock-sensor-contact'. The two sensors are at an equal distance from the source. The rock-sensor contacts tested are:

- (P1) a four-mm thick aluminum plate coupled to the rock with ultrasonic coupling gel;
- (P2) a four-mm-thick aluminum plate glued to the rock;
- (WG1) a steel rod used as waveguide (10 mm diameter, 85 mm long) glued into the rock sample at 5 cm depth;
- (WG2) a steel rod used as waveguide (10 mm diameter,

85 mm long) fixed in the rock sample using an expansion anchor at 5 cm depth;

- (WG3) a steel rod used as waveguide (10 mm diameter, 120 mm long) glued into the rock sample at 2.5 cm depth; and
- (WG4) a steel rod used as waveguide (10 mm diameter, 420 mm long) glued into the rock sample at 2.5 cm depth.

Table 2 summarizes the loss in signal amplitude measured between the reference sensor and the different contacts investigated. The smallest attenuation is observed for contacts using a thin aluminum plate. While a simple coupling of the plate on the rock using the gel appears best in this laboratory experiment, this solution does not appear feasible in the field where the rock surface at the bottom of the borehole will be uneven. In this case, the use of glue to affix the metal plate to the borehole bottom is likely a better solution. The waveguide-based contacts generally show larger attenuations. Fixing the waveguide using a glued interface extending over greater depth limits the attenuation, but likely results in less accurate estimation of the source depths. Also, the use of an extension anchor to fix the waveguide should be avoided.

Table 2. Attenuation measured for different rock-sensor contacts.

	P1	P2	WG1	WG2	WG3	WG4
Mean attenuation (dB)	1.1	1.9	2.7	8.3	10	9.7
Standard deviation	0.3	0.7	0.8	1.8	1.1	1.3

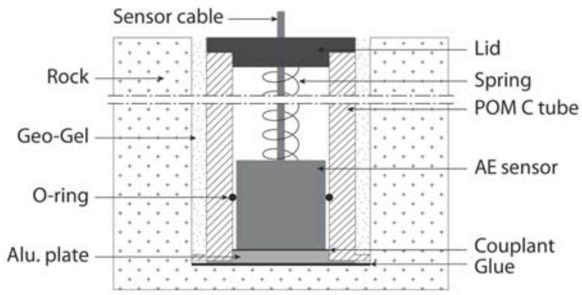

Figure 4. Installed AE-rod measurement assembly.

Design and Test of the Measurement Assembly

Based on the experimental results, we designed the final measurement assembly using the 'casing-based' solution (Fig. 4). The casing itself is made of a POM-C tube with an external diameter of 30 mm. It accommodates a piezoelectric sensor (R6alpha, Physical Acoustics Limited, UK) to record AE in the frequency range 1–150 kHz. The sensor (cylinder with 17 mm diameter, 17 mm height and a radial cable exit) is held down on the bottom assembly inside the casing using a spring. The bottom part of the casing is made of a 4-mm-thick aluminum plate. A lid with a waterproof cable port completes the surface end of the casing. The assembly is glued to the bottom of the borehole only, and the remaining space sealed with a 5-mm-thick layer of Geo-Gel injected into the void between the borehole and casing.

A freeze-thaw experiment was performed with the first prototype of this assembly to evaluate the generation of spurious AE events due to the thermal expansion of the casing itself. In this experiment, the casing containing the AE sensor and a reference AE sensor were placed in a freezer and subjected to a temperature cycle from +20°C to -15°C and back to +20°C. The amplitudes of measured AE events are shown in Figure 5. The results are difficult to interpret since the experimental setup was rather crude, and it is likely that a fraction of the measured event was generated by the freezer itself.

Four sensor-casing-assemblies were installed in a rock-wall at Jungfraujoch (3500 m a.s.l.) in Switzerland. This location was chosen for its year-round accessibility by train. The strategy chosen for this deployment was to equip two contrasting sites with measurements at two different depths each. The boreholes were drilled at differing angles, aiming at a final alignment of the sensors normal to the rock surface (Fig. 6). This reduces the disturbance caused by the boreholes in the rock closest to the AE sensors. The sensing parts of the casings are located at 10 and 50 cm depths.

The two sites equipped (Fig. 7) are only ten meters apart and show similar general characteristics: southeasterly slope aspect, 50–70° steep rock wall of granitic gneiss. The main difference between these two sites lies in the availability of liquid water. One site is on a rather dry spur-like feature, and the second site is in a gully-like depression that collects melt water from the surrounding snow patches.

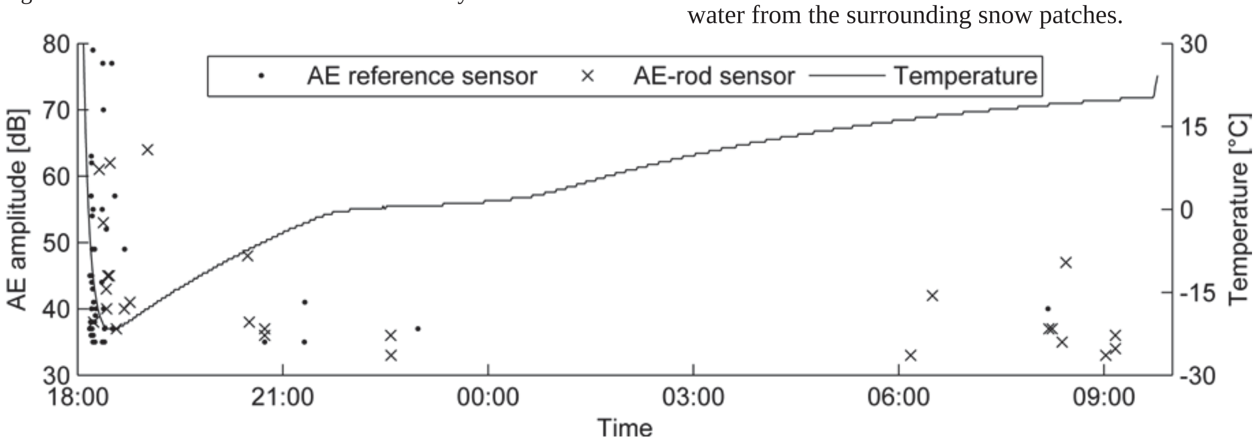

Figure 5. Result of freezer experiment: Temporal AE amplitude and temperature.

The acoustic signals are conditioned and captured by a customized 2-channel, 500 kHz sampling rate data acquisition system, the AE-Node (cf. Hunziker 2011). In addition to the AE sensors, two probes to measure temperature (Th3-s by UMS GmbH, Germany) and relative moisture by capacitance (EnviroSCAN by Sentek Technologies, Australia) at different depth were installed at each site. Data, complemented by a webcam to document surface conditions, are transmitted using a wireless sensor network customized for operation in harsh environments (cf. Beutel et al. 2009, Hasler et al. 2011). The AE-Node is designed to extract, locally store, and transmit wirelessly the AE signature from the raw acoustic signal once the signal level crosses a configurable threshold. This design and setup of the measurement system is optimized for low-power consumption and unattended operation over long periods of time in harsh environments, while giving the user access to the acquired data with low latency and means for configuration and control of the experiments undertaken.

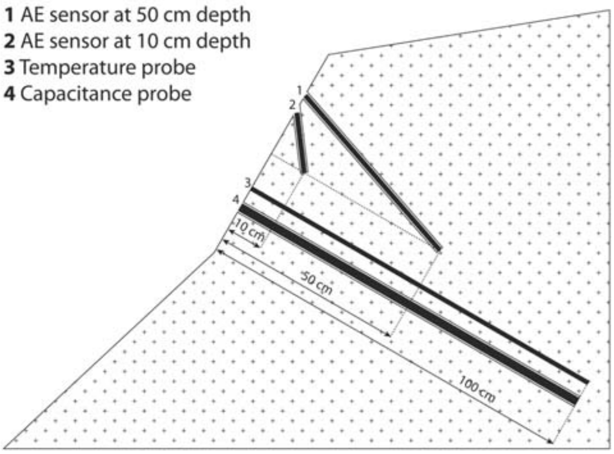

Figure 6. 2D sketch of field installation.

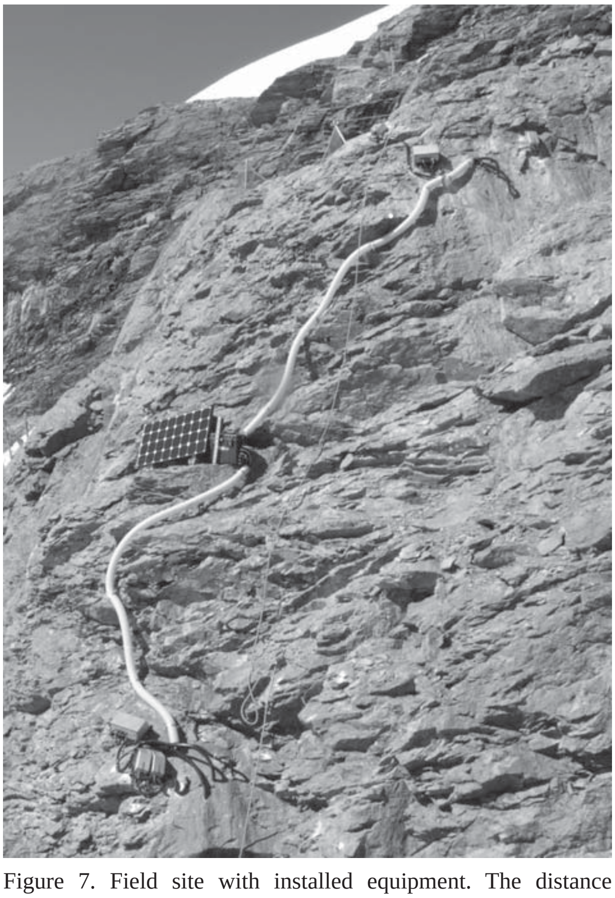

Figure 7. Field site with installed equipment. The distance between the two equipped sites is approximately 10 m.

The work reported on in this paper is the first step of an ongoing research project. The investigation of the continuous time-series of AE events currently being acquired will provide the first direct measurements of rock damage in a permafrost rock-wall. These results should help in transferring laboratory and experimental insights on frost weathering to real conditions.

Acknowledgments

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