A review on acoustic monitoring of debris flow

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Abstract

Debris flows and debris floods are processes that occur in high alpine regions with consequences on infrastructure and settlements. Recently several studies have been conducted by the authors using a new approach to gather knowledge about debris flows using a combination of two acoustic sensors: seismic sensors and infrasound microphones. Both sensors have been individually used in many previous studies. But the potential combination of infrasonic and seismic sensors for monitoring natural hazards, which could take advantage of the benefits of both sensor technologies, has not been evaluated to date.

As a consequence, in this study the most important characteristic of acoustic signals from debris flows monitored at different locations in the Austrian and Swiss Alps are summarized and possible interfering signals are presented. Additionally, the data will be compared with other measurements, such as e.g. flow depth, for the interpretation, verification and validation of the seismic and infrasonic data.
Keywords: debris flow, monitoring, infrasound, seismic waves.

1 Introduction

This study presents a comprehensive summary of debris flows monitoring using a combination of two acoustic sensors: seismometers and infrasound microphones. Both sensors have been individually used previously. Various

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earlier studies on debris flows (e.g., Okuda *et al.* [1]; Wu *et al.* [2]; Hadley and Lahusen [3]; Marchi *et al.* [4]; Arattano [5]; Huang *et al.* [6, 7]) have already shown that it is possible to detect and monitor these processes using seismic signal analysis.

Infrasound technology on the other hand has been used recently for the development of automatic detection systems for snow avalanches and debris flows (Adam *et al.* [8]; Zhang *et al.* [9]; Chou *et al.* [10]; Scott *et al.* [11]).

However, the potential combination of infrasonic and seismic sensors for monitoring debris flows, which could take advantage of the benefits of both sensor technologies, has not been evaluated to date. Both seismic and infrasonic signals are mechanical waves that are often generated by the same physical phenomena. Additionally, the Earth's surface is not opaque to mechanical waves, either those propagating upward from within the Earth's solid interior or those propagating down from the atmosphere (Arrowsmith *et al.* [12]).

The following work summarizes the most important characteristics of infrasound and seismic signals of debris flows and debris floods. For this purpose data of one debris flow (Lattenbach torrent, Austria) and on debris flood (Illgraben torrent, Switzerland) have been chosen, which can be considered as typical for the respective process.

2 Lattenbach torrent (Austria)

The Lattenbach torrent (catchment 5.3 km^2) is an observation site for debris flows operated by the Institute of Mountain Risk Engineering (BOKU, Vienna) in cooperation with the Austrian Service for Torrent and Avalanche Control (WLV) (Hübl and Moser [13]). For a detailed overview of the test site the reader is referred to Kogelnig *et al.* [14, 15] and Kogelnig [16].

2.1 Acoustic data

A debris flow event was recorded on 01.09.2008 in the Lattenbach torrent (catchment area 5.3 km^2) (fig.1). The event had a duration of 867 s (defined as time with flow depth >30 cm), a peak discharge of 380 m^3/s and a total volume of 14.000 m^3 within this time. This event has been previously discussed in Kogelnig *et al.* [14, 15] and is only shortly summarized for the purpose of this paper. Data was collected using an infrasound microphone, a geophone and two ultrasonic gauges (with an inter-distance of 47.2 m). The infrasound sensor used at this site was the Gefell WME 960H, which has a frequency range from 0.5 Hz to 20 Hz and a sensitivity of 50 mV/Pa. The geophone sensor SM4 has a frequency range from 10 Hz to 180 Hz and a sensitivity of 28.8 V/m/s. The geophone was therefore not able to register seismic signals with a frequency less than 10 Hz, resulting in missing data. The infrasound sensor, and the geophone were placed close to the channel near the upper ultrasonic gauge for better data comparison. Furthermore, Kogelnig *et al.* [14] showed that this location is optimal for both infrasonic and seismic monitoring as there is minimal background noise. A Campbell Scientific CR1000 data-logger was used with a sampling rate of 100 Hz.

A detailed description of the signal analysis methods such as time series analysis, running spectra and total spectra, that have been used, is given in Kogelnig *et al.* [14, 15] and Kogelnig [16].

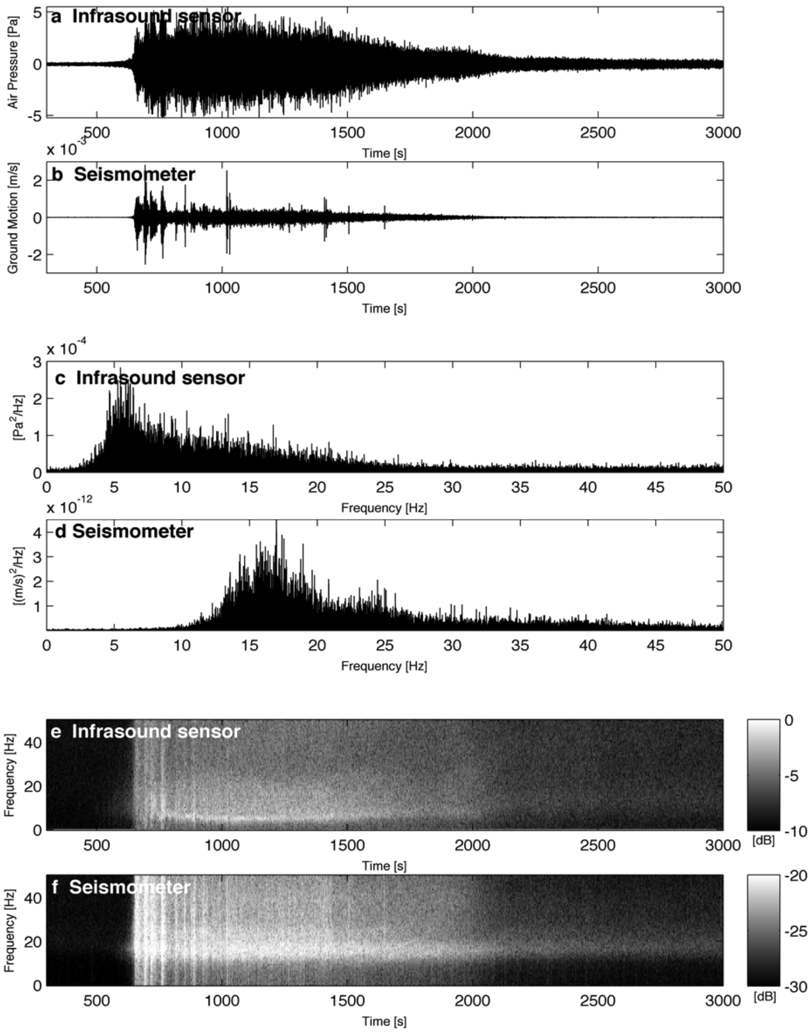

Figure 1: Infrasound and seismic (Z-component) data of a debris flow monitored at the Lattenbach test site on 01.09.2008. Signals are represented with a common base of time. (a) Infrasound time series; (b) Seismogram; (c) Total spectrum of the infrasound signal; (d) Total spectrum of the seismic signal; (e) Running spectrum of the infrasound signal; (f) Running spectrum of the seismic signal.

Figure 1 shows infrasound and seismic data of one debris flow monitored at the Lattenbach test site on 01.09.2008. In the time series of both sensors the arrival of the debris flow is characterized by a sudden increase in amplitudes at 650s (fig. 1a, b).

The maximum amplitudes of the infrasound signals produced by debris flows are up to 5 Pa and the maximum seismic amplitudes are up to 2×10^{-3} m/s. As demonstrated in Kogelnig *et al.* [14] wave packages corresponding to four surges of the debris flow can be identified in the time series between 650 s to 800 s (fig. 1a,b). Both signals present a spindle shape in the time series. The total duration of the debris flow signal in the seismic and the infrasound data is 1650 s [650 s to 2300 s]. Kogelnig *et al.* [14] further showed that the infrasound sensor detects the debris flow 90 s and the seismic sensor 50 s before it reaches the sensors.

The total spectra (fig 1 c,d) show that infrasound and seismic signals are complementary. Debris flow infrasonic signals have peak frequencies from 3 Hz to 10 Hz whereas seismic signals have peak frequencies from 10 Hz to 20 Hz.

The running spectra of the debris flow (fig. 1e, f) show a similar signal pattern in the seismic and infrasonic data. Both have a spindle shape with a rather sudden increase in frequencies and energy as the debris flow approaches the sensor location. The frequency content slowly decreases again in both sensors when the debris flow moves downstream far from the monitoring station.

3 Debris flows monitored at the Illgraben torrent (Switzerland)

In addition to the Austrian test site, debris flow monitoring was also performed at the Illgraben torrent (catchment area 9.5 km^2). This is one of the most active debris flow catchments in the Alps, where up to seven debris flow events occur per year with a great variability of flow properties.

The Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) operates the debris flow observation station at the Illgraben since the year 2000. In total 29 check damns spread across the Illgraben channel. Acoustic sensors were first installed in summer 2008 at check dam 27. For a detailed overview of the test site the reader is referred to Kogelnig *et al.* [14, 15], Kogelnig [16] and Graf *et al.* [17].

3.1 Acoustic data

One infrasound capacity microphone, developed by the Acoustics Institute at the Chinese Academy of Science (CAS), with a frequency range of 3 Hz to 200 Hz and a sensitivity of 50 mV/Pa was placed at check dam 27. Additionally, a seismic velocimeter, model GS11, was placed near the infrasound microphone. This device has a frequency range of 4.5 to 100 Hz and a sensitivity of 90 V/m/s. Data from all sensors were collected with a Campbell Scientific CR23 data-logger with a sampling rate of 50 Hz and were stored on an Xplore iX104 C3 tablet computer. Data of the infrasonic and seismic background noise at the Illgraben torrent have been presented in Kogelnig *et al.* [14]; this site generates

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greater background noise compared to the Lattenbach torrent, but the amplitudes are nevertheless low relative to the debris flow signal. The event discussed in the following occurred on 28.07.2009 and has already been discussed in Kogelnig *et al.* [15]. For the purpose of this paper it is shortly summarized.

As already explained in Kogelnig *et al.* [15] measurements provided by the WSL like bulk density (around 1600kg/m^3) and flow depth from laser sensors (flow front was small and undular) point to a debris flood like event; the impulse frequency of the geophone (operated by WSL, mounted in the concrete of check dam 27) indicates only weak activity at the flow front which could indicate that there were not many boulders or just relatively small ones. Without any visual information and given the evidence mentioned above it can be assumed that this event was a debris flood or an event that had a front like a debris flood and a body like a debris flow (private communication, Brian McArdell, WSL). Hence we refer to this event as a debris flood (according to the classification of Hungr *et al.* [18]).

The infrasound and the seismic signals are presented in fig. 2. In the time series of the infrasound sensor several high amplitude peaks are observed in the interval [1.5×10^4s to 1.8×10^4s](fig 2a). Similar peaks but with smaller amplitude are observed in the seismic data as well in the same interval (fig 2b). As explained in Kogelnig *et al.* [15] these amplitudes correspond to the passing of a thunderstorm over the area. A smooth increase of amplitudes in the interval [1.8×10^4s to 1.87×10^4s] in both sensors can be explained by a preliminary increase in discharge in the channel. In the time series of both sensors a sharp increase in amplitudes at 1.87×10^4s (fig. 2a,b) is observed. This corresponds to the passing of the main surge of the debris flood. The maximum amplitudes of the infrasound signal in the time series produced by debris flows are up to 0.6 Pa and the maximum seismic amplitudes are up to 1×10^{-4} m/s. After the passing of the main surge at 1.87×10^4s both signals present a spindle shape in the time series of the infrasound and seismic data. The total duration of the debris flood signal in the seismic and the infrasound data is 5000 s [1.8×10^4s to 2.3×10^4s]. Looking only at the signals in the time series no significant difference to the debris flow event discussed above can be identified.

The frequency distribution in the total spectra of the infrasound signal (fig 2 c,d) reveals the difference. The infrasound signals have peak frequencies from 10 Hz to 20 Hz whereas for the debris flow event discussed previously the peak frequencies range 3 Hz to 10 Hz. These values hint that the characteristic of the process must be different. The peak frequencies in the seismic total spectrum are above 20 Hz (fig. 2d), which, similar to the infrasound frequency content, is higher than that of the Lattenbach signal (seismic range 10 Hz to 20 Hz).

The running spectra of the debris flood (fig. 2 e,f) show a similar signal pattern in the seismic and infrasonic data. Both have a sudden increase in frequencies and energy as the main surge of the debris flood passes the sensor location. The frequency content and the energy slowly decrease again in both sensors as the debris flood moves downstream far from the monitoring station.

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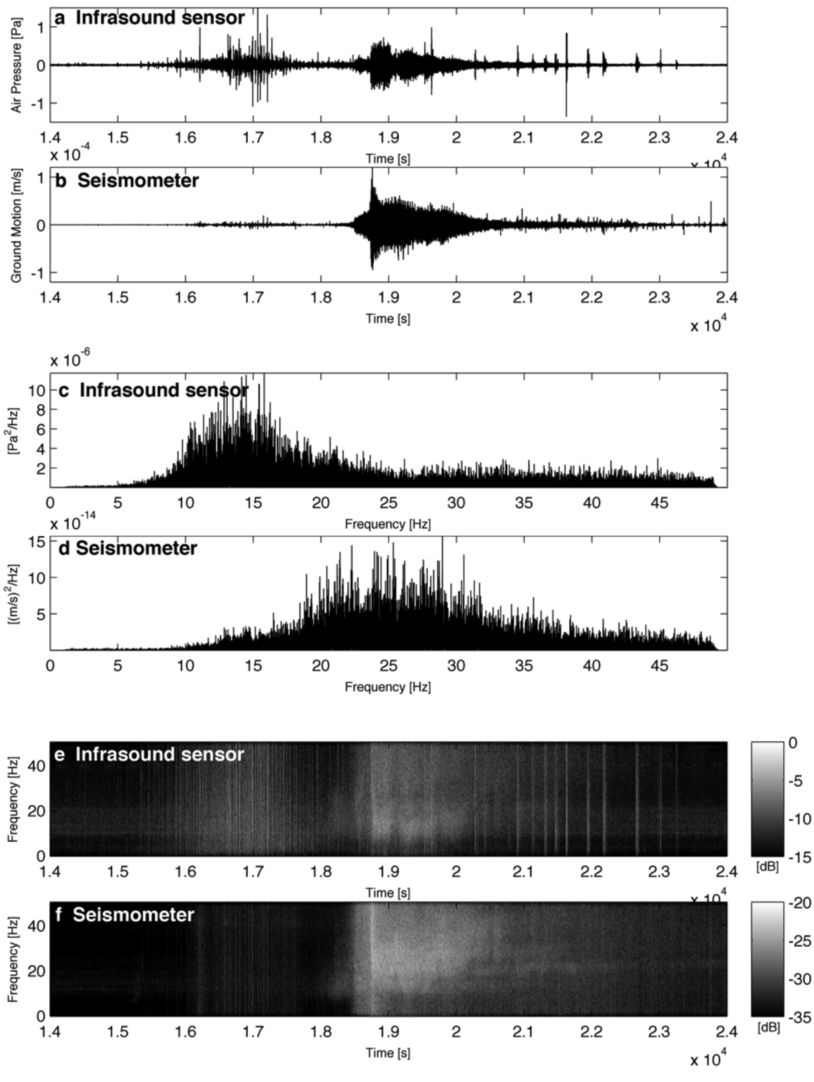

Figure 2: Infrasound and seismic (Z-component) data of a debris flood monitored at the Illgraben test site on 28.07.2009. Signals are represented with a common base of time. (a) Infrasound time series; (b) Seismogram; (c) Total spectrum of the infrasound signal; (d) Total spectrum of the seismic signal; In order to show only the debris flood frequency content a time window from 1.8-2.2×10^4 was chosen for the computation of the total spectra (e) Running spectrum of the infrasound signal; (f) Running spectrum of the seismic signal.

4 Conclusions

This paper presents a review on acoustic monitoring of debris flows based on previous studies conducted by the authors (Hübl *et al.* [19], Kogelnig *et al.* [14, 15] and Kogelnig [16]). It analyses the application of infrasound and seismic sensors for monitoring and characterization of debris flows. For the first time, in-depth studies combining the infrasound and seismic wave fields generated by alpine mass movements have been carried out. We showed that the combination of infrasound and seismic sensors is a valuable tool for monitoring debris flows and that: i) infrasound and seismic signals are correlated with each other and also with other measurements (e.g. flow depth for debris flows), ii) the combination of both sensor technologies increases the detection probability.

However, the application of seismic and infrasound sensors for monitoring alpine mass movements is not a straightforward task. Thorough investigations of the study site and the background noise characteristics are necessary to determine the suitability for acoustic monitoring. Understanding the propagation and attenuation mechanisms of seismic and infrasonic waves in the study conditions is crucial for the interpretation of the recorded seismic and infrasonic signals. The equipment and the placement of the sensors have to be chosen carefully, as shown by the results obtained in China (see Kogelnig *et al.* [15]).

Table 1: Summary of the recorded maximum amplitudes (MA) of the seismic signals (m/s) and infrasound signals (Pa) of debris flows. Also summarized is the total duration (s) based on the seismic and infrasound data, the peak frequency content (Hz) and the typical pattern in the running spectra (RS).

	Debris Flows
MA_{IS}	1 Pa to 4.8 Pa
MA_{SEIS}	10^{-3} m/s
Total Duration	1500 s to 5500 s [(a)]
Peak Freq. $_{IS}$	3 Hz to 10 Hz 10 Hz to 20 Hz [(a)]
Peak Freq. $_{SEIS}$	10 Hz to 20 Hz
Pattern in RS_{IS}	Spindle shape
Pattern in RS_{SEIS}	Spindle shape

[(a)] Debris flood events monitored at Illgraben test site.

Previous studies (Hübl *et al.* [19], Kogelnig *et al.* [14, 15] and Kogelnig [16]) recorded infrasound and seismic data of several torrential processes (debris flows and debris floods) in Switzerland and Austria. In addition, numerous sources of interfering signals were studied and discussed in Kogelnig [16]. The detailed analysis of all the seismic and infrasonic signals allowed not only to find a characteristic evolution in the time and frequency domain for the specific processes studied, but also to make a clear differentiation from interfering signals. The studies confirmed that debris flows produce seismic and infrasonic signals characteristics that are reproducible at very different experimental sites and under different environmental conditions.

Table 5 summarizes the main characteristics of infrasound and seismic data of debris flows in view of the other common sources of infrasound signals, which have been presented in Kogelnig [16].

Besides the purpose of detection, seismic and infrasonic signals were used to determine relevant physical information related to the dynamics of the process.

For torrential processes it has been shown that the frequency content of the infrasound signals vary between debris flows and debris floods. Debris flows generally have lower peak frequencies in the infrasound signal (around 5 Hz) compared to debris floods (>7 Hz). The amplitude and frequency content of the seismic and infrasound signals increase as the debris flow moves towards the sensors. During the passage of the debris flow, the ultrasonic gauges identified several surges. The time series and the running spectra of the seismic and infrasonic data also recognize these surges. The relative detection capabilities of both sensors are strongly dependent on the terrain. At the Lattenbach torrent the infrasound sensor detects the debris flow before the seismic sensor, whereas at the Illgraben the opposite was observed (Kogelnig *et al.* [14]). We believe that high mountain ridges, as is the case at the Illgraben, produce a natural sound barrier with an acoustic shadow zone behind. If the infrasound sensor is placed within this shadow zone the forecast time is significantly reduced. Seismic sensors provide signals in near real time due to the high seismic speed in the ground, but they are more sensitive to signal attenuation effects, strongly depending on the characteristics of the ground and the distance between source and receiver.

In summary, the initial motivation for this study, i.e. to investigate for the first time a combination of infrasound and seismic sensors for monitoring alpine mass movements, showed promising results. The combined analysis of the emitted infrasonic and seismic wavefield gives further insights on the process monitored.

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