DOI: 10.4408/IJEGE.2011-03.B-062

A STUDY OF INFRASONIC SIGNALS OF DEBRIS FLOWS

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ABSTRACT

Mass movements such as debris flows, rock fall and snow avalanches are sources of sub-audible sounds in the low frequency infrasonic and seismic spectrum. Recent studies indicated that debris flow-generated signals are of significant amplitude and occupy a relatively noise free band in the low frequency acoustic spectrum. Infrasound signals have the ability to propagate kilometres from the source, thereby allow monitoring of mass movements from a remote location. This study presents debris flow monitoring at four international sites - Lattenbach, Tyrol (Austria), Illgraben, Valais (Switzerland), and the MiDui and GuXiang Glacier, Tibet (China). The infrasound sensors used were the Chinese sensor (DFW I-III) or the German sensor (Gefell WME 960 H). The results show that debris flows emit detectable low frequency infrasonic signals (1-20 Hz) that are correlated to seismic signals. The infrasound sensors detect the phenomena before it reaches the sensors, depending on the landscape, distances and the sensitivity of the equipment.

INTRODUCTION

Rapid mass movements (debris flows or snow avalanches) are periodic or episodic phenomena that present a hazard for people and property in inhabited alpine areas. Although efforts to develop debris flow monitoring or warning devices have increased in the last decades (Arattano, 1999; Itakura *et alii*, 2005; LaHusen, 2005; Badoux *et alii*, 2009) further research is needed and only few studies exist of infrasound monitoring of such events (Zhang *et alii*, 2004; Chou *et alii*, 2007; Hübl *et alii*, 2008; Kogelnig *et alii*, in press). Infrasound signals (frequency range 0.01-20 Hz) are longitudinal pressure waves that travel through the air at a speed of 343 m/s, which is the same as that of audible sound. Infrasound signals can propagate over long distances in the atmosphere with little attenuation. This is due to selective frequency absorption of sound waves in the atmosphere - higher frequencies (e.g. audible) are absorbed more readily than lower frequencies (e.g. infrasound) (Pilger *et alii*, 2009). For debris flow monitoring seismic waves as well as infrasound, both have benefits and drawbacks. The latter is mostly noise induced from wind or human activities that mask the debris flow signal. The benefits include no structural need for sustainability and monitoring from a remote location not affected by the process activity. The quality of monitoring results will depend on the relative positioning between the mass movement and the sensors as well as the specific characteristics of the site (e.g. topography).

The aim of this study is to present further results of infrasound monitoring of debris flows at four international sites and to illustrate the potential of infrasound monitoring of alpine mass movements. The study sites included the Lattenbach torrent (Tyrol, Austria), the Illgraben torrent (Valais, Switzerland), the MiDui Glacier (Tibet, China) and the GuXiang Glacier (Tibet, China). The specific equipment, setup and sensor placement differed between sites. Where available, seismic signals and flow depth data were used for comparison, correlation and validation of the infrasound data.

LATTENBACH (AUSTRIA)

A debris flow event was recorded on 01.09.2008 in the Lattenbach torrent (catchment area 5.3 km^2) (overview see 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 14000 m3 within this time. For further details of this event, the reader is referred to Kogelnig *et alii* (in press). 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 to 20 Hz and a sensitivity of 50 mV/Pa. The geophone sensor SM4 has a frequency range from 10 to 180 Hz and a sensitivity of 28.8 V/m/s. The geophone was therefore not able to register those seismic signals with a frequency less than 10 Hz, resulting in missing data. The infrasound sensor was placed in the proximity of the upstream ultrasonic gauge and the geophone for better data comparison. Furthermore, this location has previously been shown to be optimal for both infrasonic and seismic monitoring as there is minimal background noise (Kogelnig *et alii* in press). A Campbell Scientific CR1000 data-logger was used with a sampling rate of 100 Hz. The signals were analysed with Running Spectra (RS), which present the temporal evolution of the frequency content of a signal, using the Short Time Fourier transformation with a Hanning Window (length 128 samples) and an overlap of 50%. Furthermore, an analysis with Power Spectra (PS) were used, which show the frequency content of a stationary signal. Debris flows are generally described as moving downhill in a series of waves or surges, whereby the flowing body has a steep front with higher material content and the flowing tail has a more gradual slope and higher water content (Iverson, 1997). These particular characteristics, which are common to all debris flows, can also be seen in the flow height data from the ultrasonic gauges as well as the seismic and infrasonic data from this event (Fig. 2 and 3, rectangles).

A more detailed explanation is given in Kogelnig *et alii* (in press). The acoustic sensors detect the debris flow before it reaches the sensors - 50 s earlier in the case of the geophone and 90 s earlier for the infrasound sensor. Using an average flow velocity of 6 m/s (obtained from the ultrasonic gauges), these time differences correspond to 300 m and 540 m, respectively (Fig. 1, B and C). The peak signal frequencies seen during this event were approximately 6 Hz for the geophone and 17 Hz for the infrasound sensor (Fig. 2 and 3). It must be noted that the geophone device has a cut-off frequency of 10 Hz; however, it is expected that infrasonic waves have a lower frequency content compared to seismic waves, and there is generally little signal energy above 15 Hz in infrasound. According to Chou *et alii* (2007), peak frequencies of infrasound debris flow signals are thought to be correlated to the flow characteristics.

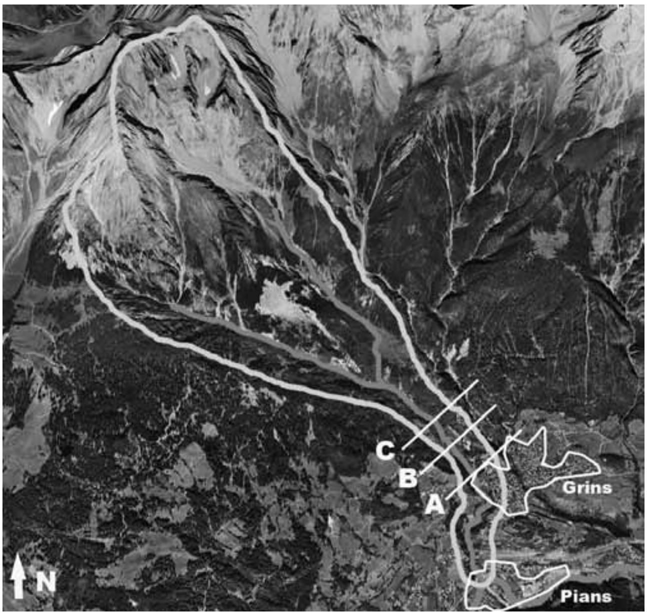

Fig. 1 - Overview of Lattenbach torrent - the catchment area and the affected villages of Grins and Pians are highlighted. The geophone detected the debris flow 300 m upstream (B) and the infrasound sensor 540 m upstream (C) of the actual sensor location (A) (Source: Google Earth)

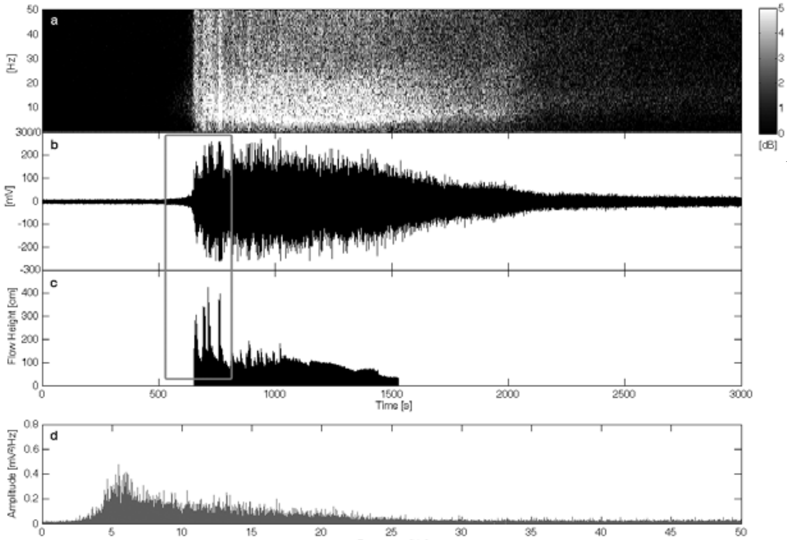

Fig. 2 - RS (a), time series (b), flow depth (c) and PS (d) of the infrasound signal during a debris flow on 01/09/08 in the Lattenbach torrent. Different debris flow surges are marked by the rectangle. The initiation time corresponds to Fig.3. Infrasound signal in mV, sensor sensitivity 50mV/Pa

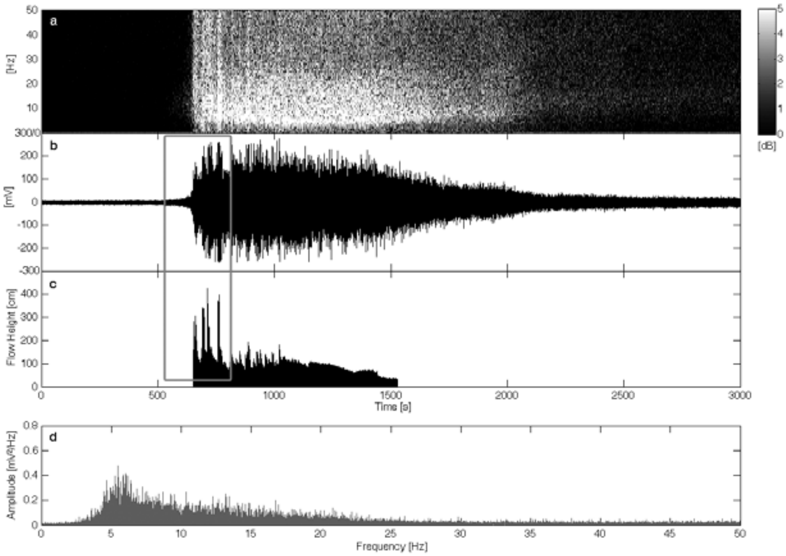

Fig. 3 - RS (a), time series (b), flow depth (c) and PS (d) of the seismic signal during a debris flow on 01/09/08 in the Lattenbach torrent. Different debris flow surges are marked by the rectangle. The initiation time corresponds to Fig. 2. Geophone signal in mV, sensor sensitivity 28.8V/m/s

The following sections provide a comparison of peak frequencies during different debris flow events in other countries.

ILLGRABEN (SWITZERLAND)

The Illgraben torrent is famous for its frequent sediment transport and debris flow activity. This may be accounted for by both its situation in an area of highly fractured bedrock (Badoux *et alii*, 2009) and its size (9.5 km^2). In total there are 29 check dams located over the course of the torrent (Fig. 4). Check dam 1 has the greatest vertical height (48 m), whereas dams 2 to 29 have heights varying between 1 and 7 m and several are either covered by sediment deposits or are destroyed. Two infrasound capacity microphones, developed by the Acoustics Institute at the Chinese Academy of Science (CAS), were placed 38 m apart in the proximity of check dam 27. These devices have a frequency range of 3 to 200 Hz and a sensitivity of 50 mV/Pa. Unfortunately, this setup was not ideal as the distance between sensors was inadequate to show a difference in arrival time within the acoustic signals. Data will therefore be presented for the upstream microphone only. Additionally, a seismic velocimeter, model GS11,

Fig. 4 - Overview of the Illgraben torrent - the catchment area and the boarder between mountains and Rhône valley are highlighted. The infrasound sensor detects the debris flow 1500 m upstream (A) of check dam 27 and the seismic sensor 2000m upstream (B) (Source: Google Earth)

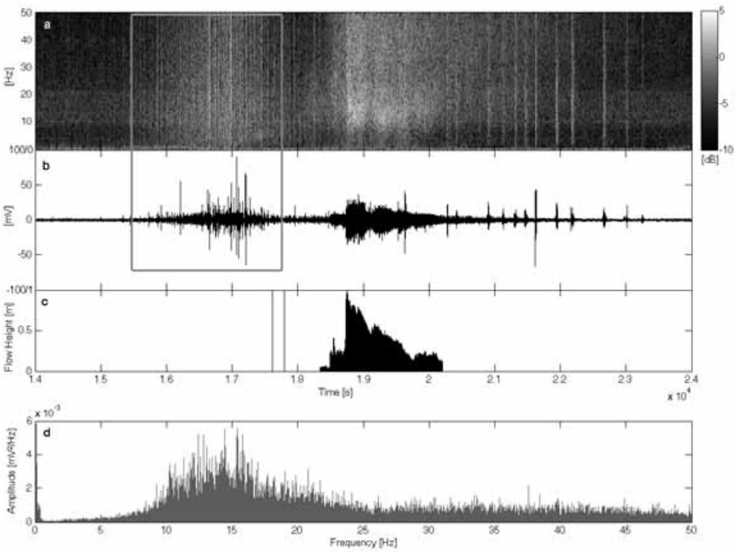

*Fig. 5 - RS (a), time series (b), flow depth (c) and PS (d) of the infrasound signal during a debris flood on 28/07/09 in Illgraben torrent. In order to show only the debris flood frequency content a time window from 1.8-2.2*104s was chosen for the computation of the PS. Infrasound signal associated with a thunderstorm in the area are marked by the rectangle. The passing of the debris flood at check dam 1 and check dam 10 is marked by the vertical lines in the flow depth graph. Infrasound signal in mV, sensor sensitivity 50mV/Pa*

was placed near the upstream 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 three acoustic 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. Finally, ultrasonic gauges were placed at check dams 1, 10 and 27 to monitor flow depth (sampling rate 1 Hz). These gauges were operated by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

Data of the infrasonic and seismic background noise at the Illgraben torrent have been presented in KOGELNIG *et alii* (in press); this site generates greater background noise compared to the Lattenbach torrent, but the amplitudes are nevertheless low relative to the debris flow signal. The torrential process discussed in this paper occurred on 28.07.2009. Unfortunately no video data is available of this event. Other measurements provided by the WSL like bulk density (around 1600kg/m^3) and flow depth from laser sensors (flow front was small and

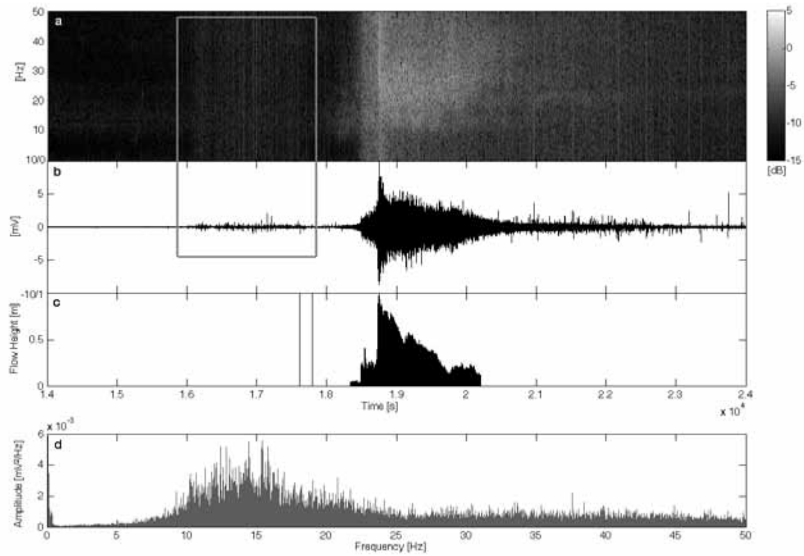

*Fig. 6 - RS (a), time series (b), flow depth (c) and PS (d) of the seismic signal during a debris flood on 28/07/09 in the Illgraben torrent. In order to show only the debris flood frequency content a time window from 1.8-2.2*104s was chosen for the computation of the PS. Seismic signal associated with a thunderstorm in the area are marked by the rectangle. The passing of the debris flood at check dam 1 and check dam 10 is marked by the vertical lines in the flow depth graph. Geophone signal in mV, sensor sensitivity 90V/m/s*

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. Hence in this paper we will refer to this event as debris flood (according to the classification of Hungr *et alii*, 2001).

The infrasound signal is shown in Fig. 5 and the seismic signal in Fig. 6. From the ultrasonic gauges it is known that the main surge of the debris flood passed check dam 1 at 11:18:00 pm (accuracy of +/- 1 min due to installation issues), check dam 10 at 11:21:00 pm and check dam 27 at 11:39:42 pm. This corresponds to a flow duration of 1122 s between dams 10 and 27, and given that this is a known distance of 2656 m, the average flow velocity in this section can be calculated as 2.3 m/s.

The RS of the infrasound signal shows the arrival of the first debris flood signal at 11:28:49 pm (Fig. 7). There is also an observable increase in amplitude in the time series in this section. This occurs approximately 653 s before arrival at check dam 27. Assuming the above calculated average speed of 2.3 m/s, this time point corresponds to a distance of 1500 m, which happens to be the topographical transition between the mountains and valley near the Bhutan Bridge (Fig. 4, A). Previous work (Kogelnig *et alii*, in press) also reported that the infrasound microphone, when placed at check dam 27, detects the torrential processes at this location.

Infrasound signals generated from debris flows are believed to be produced by the violent surge front and the collisions (or abrasion) between the flow and the channel loose boundary (Chou *et alii*, 2007). Previous studies (Zhang *et alii*, 2004; Hübl *et alii*, 2008) reported that viscous debris flows recorded in the Jinagjia Gully (China) have a frequency content of 6-10 Hz. In contrast, Chou *et alii*, 2007 monitored stony debris flows in Houyenchan (Taiwan) and reported frequencies between 5-15 Hz and concluded that viscous flows emit lower frequencies than stony flows.

The PS of the infrasound signal indicates that the main frequency content from this debris flood was between 10 and 20 Hz. This differs from those results seen at the Lattenbach torrent (peak frequency ca. 6 Hz) and those reported by Kogelnig *et alii* (in press) for a previous event at the Illgraben (31.08.2008, peak frequencies from 3 to 8 Hz). These results hint that debris floods produce higher peak frequencies (10-20 Hz) than debris flows (< 10 Hz).

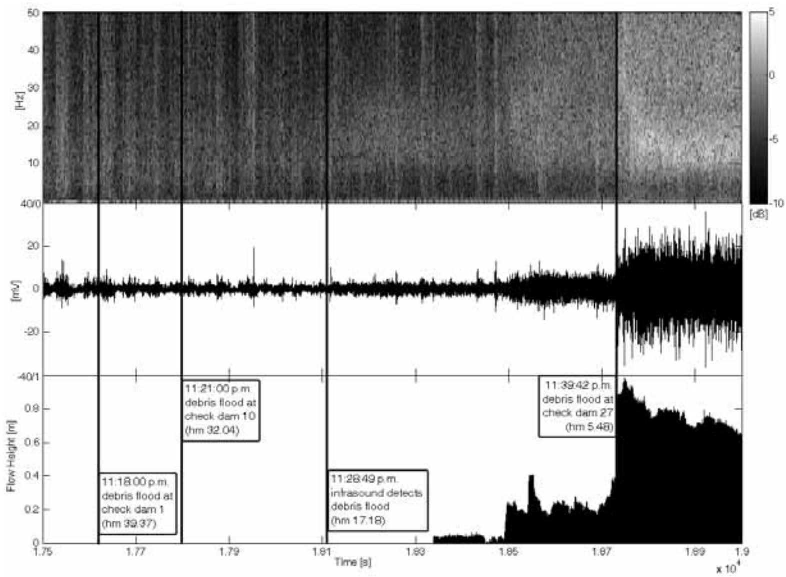

Fig. 7 - Magnified section of Fig. 5; the infrasound sensor detects the debris flood ca. 377s before it passes the sensor

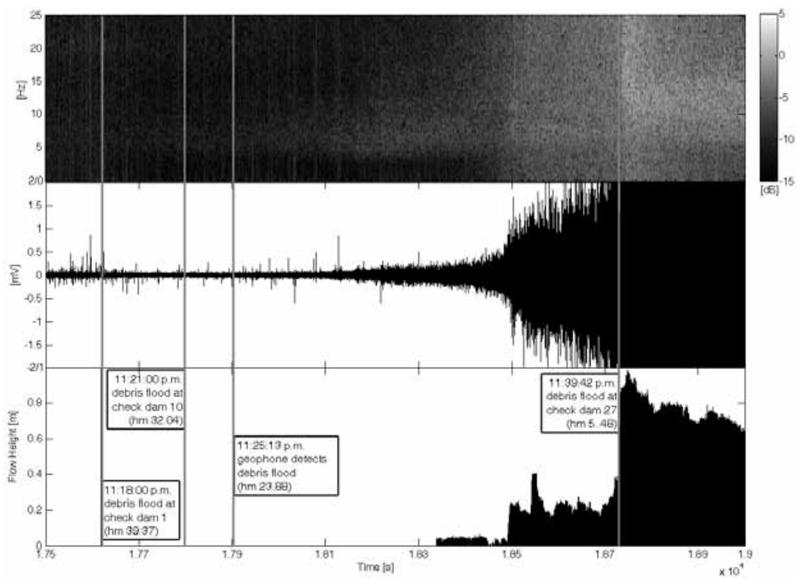

Fig. 8 - Magnified section of Fig. 6; the geophone detects the debris flood ca 593s before it passes the sensor

The RS of seismic data shows the arrival of the first debris flood signal at 11:25:13 pm (Fig. 8), which is 869 s before the debris flood passes check dam 27 and 216 s before the infrasound sensor detects the event. Applying the above distance calculation (i.e. assuming a constant flow velocity of 2.3 m/s) this corresponds to a distance of 2000 m (Fig. 4, B).

The peak frequency content in the seismic PS was 20 to 30 Hz (Fig. 6), which, similar to the infrasound frequency content, was higher than that of the Lattenbach torrent (seismic range 10-20 Hz).

GUXIANG GLACIER (CHINA)

The GuXiang Glacier is well known for its frequent debris flow occurrences. The first sizeable event was in 1953 - the event had a peak discharge of 12600 m^3/s and a total volume of thirty million cubic metres. The flow structure was a mixture of fine sediment, stones and boulders. This event blocked the Podou Zhangpu River and formed the lake as it is now (Fig. 9). The catchment area is 24 km^2 and debris flows can be classified as viscous. The infrasound monitoring unit DFW-I III (which includes a microphone and a data-logger) was installed

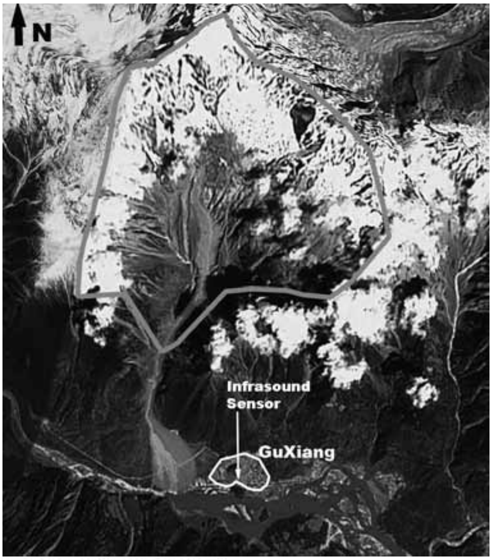

Fig. 9 - Overview of the GuXiang Glacier - catchment area, debris flow channel, Podou Zhangpu River and neighbouring town with sensor location indicated. Clearly observable is the lake formed by the event in 1953 (Source: Google Earth)

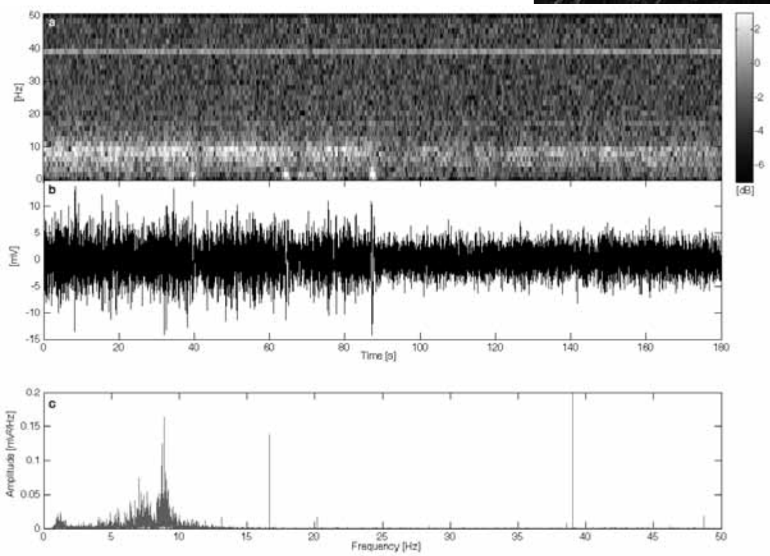

Fig. 10 - RS (a), time series (b) and PS (c) of the infrasound signal during a debris flow on 12/09/07 flow at GuXiang Glacier starting at 01:30:12am. Infrasound signal in mV, sensor sensitivity 50mV/Pa

at this site. The sampling rate of the unit is 100 Hz. The data-logger was developed in 2004 by the Institute of Mountain Hazards and Environment, the CAS and the Southwest Jiao Tong University. The microphone was created by the Acoustics Institute at the Chinese Academy of Science (CAS) and is a further development of the original device described in Zhang *et alii* (2004). It has a frequency range of 3 to 200 Hz and a sensitivity of 50 mV/Pa. For safety and convenience reasons, the equipment had to be placed in the cultural room office in the GuXiang village, approximately 5 km east of the debris flow channel (Fig. 9). This setup location is less preferable compared to the European sites and resulted in lower data resolution due to both signal attenuation (an effect of distance source sensor and building interference) and increased background noise. The infrasound signal over 180 s is shown in Fig. 10. Other measurements for comparison to this data were not available. Local witnesses provided anecdotal evidence of event time and date. The RS of the infrasound shows a constant signal in the frequency range from 5 to 10 Hz (Fig. 10), which is assumed to be associated with the debris flow. This frequency range is also observable in the PS. These results correspond to the infrasonic data reported by Zhang *et alii*. (2004) and Hübl *et alii*. (2008) for viscous debris flows in the Jinagjia Gully

Fig. 11 - Overview of the MiDui Glacier - catchment area (black) debris flow channel and the Podou Zhangpu River. The distance between the infrasound sensor (A) and the area of debris flow origin (B) is 7.5km (Source: Google Earth)

(China). There is no observable increase in amplitude in the time series nor an increase in the frequency in the RS (Fig. 10), as was the case for the Lattenbach and Illgraben torrents. An increase in amplitudes and frequencies in the infrasonic signal is observed when a debris flow is moving toward the sensor, and the highest values are seen when the flow passes the sensor (Kogelnig *et alii*, in press). The absence of these increases may be due to the source-sensor distance. The placement indoors or the rheology of the flow could be further explanations for the constant signal amplitude. There are no expected differences due to the infrasound microphone, as this same device was used at the Illgraben torrent and only the data-logger differs.

MIDUI GLACIER (CHINA)

The MiDui Glacier is one of the most famous glaciers in Tibet. It is situated east of the GuXiang Glacier, approximately 131 km upstream in the Podou Zhangpu River, and has a catchment area of 123.8 km^2. The channel has a N-S orientation and flows into the south bank of the Podou Zhangpu River (Fig. 11). The debris flows occurring here originate at the glacier. The first event occurred in 1988, resulting from a glacial lake outburst. The peak discharge was 1270 m^3/s. The river was blocked, the highway was destroyed and downstream villages and cities were flooded.

Since 1988 several smaller viscous debris flows have occurred almost yearly, but they did not reach the monitoring point (Fig. 11, A).

As with the GuXiang Glacier, the infrasound monitoring unit DFW-I III was used (frequency range of 3 to 200 Hz, sensitivity of 50 mV/Pa and sampling rate of 100 Hz). For safety purposes, the equipment had to be placed in the local travel office which is close to the debris flow channel. Fig. 12 and Fig. 13 provide the infrasonic data recorded with the DFW-I III unit. As this device was developed for warning purposes, recording is initiated only if the amplitudes reach over a threshold value (3 mV). Fig. 12 illustrates a 100 s window with recordings that are related to debris flow activity in the channel. Fig. 13 provides a 17 s window that shows one debris flood surge (according to local witnesses). An increase in amplitude is observable in the time series as well as a change in the frequencies in the RS. More interestingly, in the PS the main frequency content has shifted to 10 to 20 Hz (similar to the Illgraben, Fig. 5) in comparison to the frequency shown in the larger time window (Fig. 12, 5-10 Hz). No firm confirmation can be given due to a lack of supplementary data; it can only be assumed that the frequencies reflect a difference in flow characteristics (i.e. debris flood) of the single surge.

CONCLUSIONS

Infrasound monitoring of debris flows at different locations in Europe and China are presented in this study. The infrasound data could be correlated with seismic recordings and flow height measurements for the Lattenbach (Austria) and Illgraben (Switzerland) torrents. In all cases, the infrasound device was able to detect the event before passing the sensor location. At the Lattenbach torrent, the infrasound sensor detected the debris flow before the geophone (cut-off frequency 10 Hz), whereas the opposite was seen at the Illgraben torrent (geophone cut-off frequency 4.5 Hz). Further studies are required to clarify the relative detection capabilities of these sensors.

Data analysis for the two sites in China was more

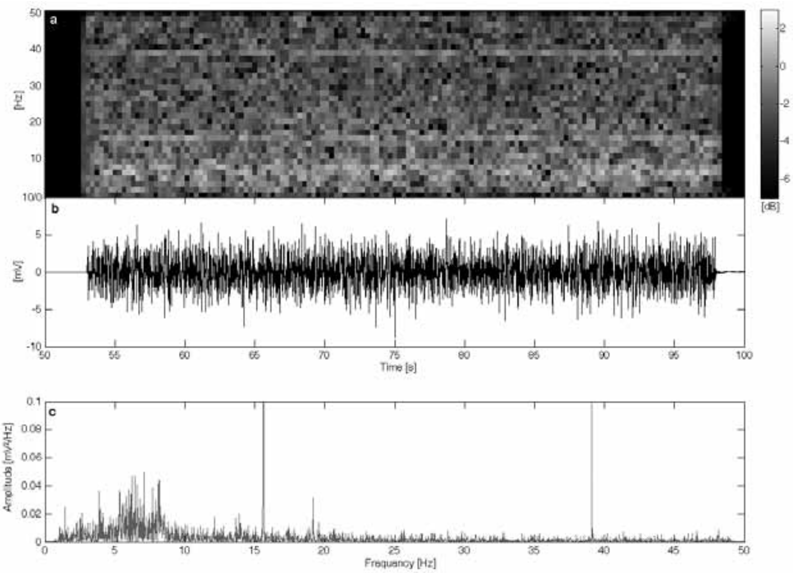

Fig. 12 - RS (a), time series (b) and PS (c) of the infrasound signal during a debris flow on 10/08/09 flow at MiDui Glacier starting at 07:35:36am. Infrasound signal in mV, sensor sensitivity 50mV/Pa

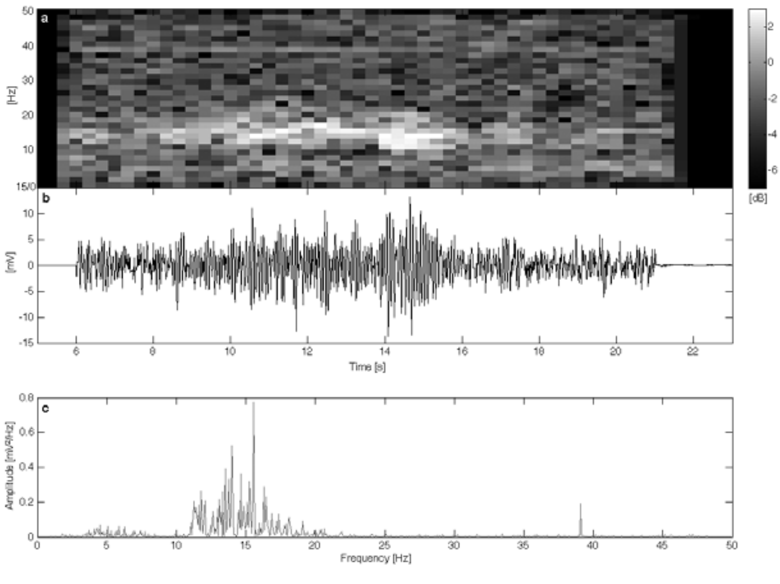

Fig. 13 - RS (a), time series (b) and PS (c) of the infrasound signal of a single surge during a debris flood on 05/09/08 at MiDui Glacier starting at 09:07:38pm. Infrasound signal in mV, sensor sensitivity 50mV/Pa

challenging and reference data were unavailable. Furthermore, the DFW-I III is a warning device that initiates recording only after the breach of a specific amplitude threshold and, as such, there is no knowledge of signal patterns below this threshold. For further studies at these two sites it is recommended to employ a seismic sensor in addition to the infrasound sensor, relocate the sensors to an outdoor location and implement a continuous recording scheme. These sites are promising and the warning device is nevertheless a powerful tool for debris flow alarming systems.

The preliminary results indicate that a combination of infrasound and seismic sensors and an analysis of the frequency evolution of the signal (RS) are the most promising for monitoring torrential hazards. Moreover, interfering noise in the signal arising from a local thunderstorm are presented in the Illgraben data. Variations in predominant infrasound and seismic frequencies of over 15 Hz were seen between study locations. It can be concluded that debris flows emit infrasound signals with a lower frequency spectrum (<10 Hz) than debris floods (>10 Hz), and that the frequency range is dependent on study site characteristics, sensor location and process characteristics.

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