Scientific Report GEFSC Loan 950

Seismic Monitoring of Geomorphological Processes: Tracking Mobile Sources

Arnaud Burtin and Niels Hovius
University of Cambridge, now at the Helmholtz GeoForschungsZentrum Potsdam, Germany

Abstract

With a 2-Dimensonal (2-D) seismological array deployed in the Illgraben catchment (Switzerland) during the of summer 2011, we have detected and located with a high spatio-temporal resolution the geomorphic processes (mainly rockfalls and debris flows) that were triggered during rainstorms over a 100-day period. We succeeded in following the effects of a rock avalanche in the upper catchment and that evolved downstream into a debris flow. Its propagation gave rise to a secondary hillslope event (bank collapse). Such a sequence highlights the potential of seismic monitoring to survey in near real-time the two-way link that exists between hillslopes and channels. Further analysis of the seismic signals allowed us to extract characteristics of channel flows (velocity, rheology and energy) and their downstream evolution. Our results indicate that seismic monitoring can give substantial new insights into hillslope and channel processes and help enhance natural hazard early warning systems. Further development of the seismic surveying of surface processes will enable the tracking of mobile sediments in a landscape.

Background

Geomorphic processes operating on Earth's surface erode and deposit sediment, causing redistribution of soil materials and nutrients, building environments for human habitation whilst jeopardizing life and economic activity elsewhere, and changing the physical landscape. Climate is a key driver of geomorphic processes, for example through the role of rainfall in erosion. Many hillslope mass wasting processes such as landslides and debris flows are triggered by intense or prolonged rainfall, and fluvial sediment transport is controlled by the translation of precipitation into runoff and channel flow. The ongoing change of climate can involve large changes of patterns and intensities of precipitation. In many uplands and mountain areas rates and locations of avalanching and landsliding may change, steep channels can become more prone to debris flow incidence, and upland rivers may have larger and more frequent floods, causing increased bedload transport, reworking of river beds. The management and mitigation of effects of climate change require detailed knowledge of the geomorphic response to changes in precipitation. This is obtained through direct observation. Current monitoring of mass wasting on hillslopes and sediment transport in channels uses geodesy [Malet et al., 2002], wire sensors, photocells, ultrasonic, infrasonic [Zhang et al., 2004] and ground vibration sensors such as geophones [Huang et al., 2007; Badoux et al., 2009], and hydrometric gauges [Lin et al., 2008]. These tools are typically targeted at specific locations that are thought to be especially hazardous, or located in channels well downstream of the point of initiation of an event. Consequently, they afford limited spatial coverage or resolution. Better spatial coverage is given by airphotos and satellite images, but they are not normally acquired at a sufficiently high frequency to detect and time all events [Brardinoni et al., 2003]. An optimal monitoring technique would allow the rapid detection of all significant geomorphic events in a landscape, and assessment of their location, nature and magnitude.

Surface processes generate ground vibrations that can be recorded by nearby seismic stations. The analysis of waveforms, in time and frequency, can be used to detect, locate and characterize these various processes. A temporary seismic experiment (Hi-CLIMB [Nábelek et al., 2009]) in Nepal has shown the potential of seismology to monitor and locate river sediment transport as well as debris flows [Burtin et al., 2008; 2009; 2010]. With other specific experiments [Burtin et al., 2011; Hsu et al., 2011], the utility of seismological techniques to monitor the landscape dynamics has been confirmed. A variety of seismic signals are observed for different geomorphic processes [Helmstetter and Garambois, 2010; Burtin et al., *in revision*]. These complexities make it possible to study not only individual processes but also their interactions and also to track sediment from sourcing to deposition. To explore the details of such processes, we have instrumented a small catchment with intense and variable geomorphic activity using instruments from the NERC equipment pool. The catchment in question is the Illgraben (< 10km^2), located in the Canton of Valais, Switzerland. The Illgraben produces several debris flows each year from a steep catchment with frequent avalanches and rockfalls [Badoux et al., 2009; Berger et al., 2011]. The catchment is monitored by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), producing comprehensive records of hydrological and geomorphic events and their meteorological context.

Survey procedure

We deployed an array of 10 seismic stations in the Illgraben catchment between the 24th of June and the 28th of September 2011 (Fig.1). Among the installed seismic instruments, 6 sensors were CMG6-TD from the SEIS-UK Equipment Pool, 3 others were LE3D-S with TITAN digitizers and the last station was a CMG-40T with a RT130 digitizer, all borrowed from the Université de Strasbourg (École et Observatoire des Sciences de la Terre). The geometry of the network was designed to resolve distributed slope activity and channel processes. Therefore, seven stations were deployed around the Illgraben catchment (IGB03 to IGB08 and IGB10), one inside the catchment (IGB01), and two along the central debris flow channel (IGB02 and IGB09). At each site, a 0.5 m deep pit was excavated and installed a levelled sensor inside a waterproof bag. For instruments in grassland, a fence was built around the equipment to avoid disturbance by cows. Station power was provided by a 52Ah battery connected to a 20W solar panel from SEIS-UK. We recorded data in continuous mode at a sampling rate of 200 SPS for CMG6-TD instruments and 125 SPS for TITAN stations due to digitizer capacity. We visited all sites once in July and once in August to check the functioning of stations, to download the recorded data and to empty the disk. All seismic data were converted to SAC format and processed with MATLAB software.

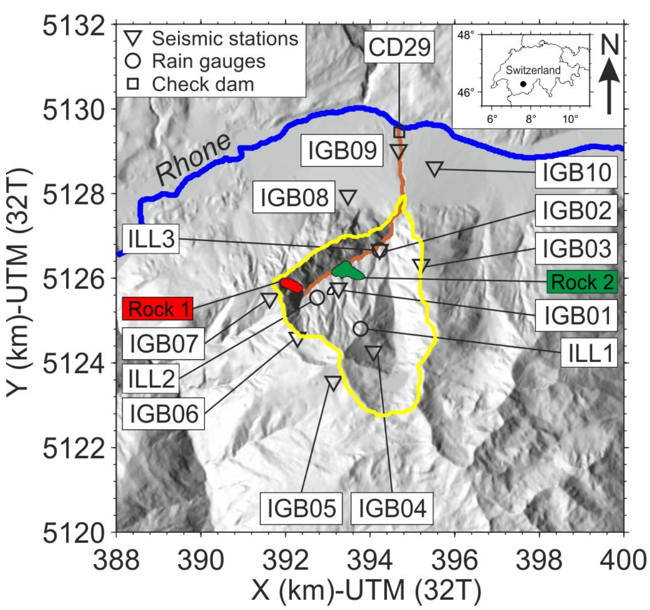

Figure 1: Location of the Illgraben catchment (~10 km^2, outlined in yellow) in Switzerland (dot in the inset map) and of the seismological stations deployed there during summer 2011 (inverse triangles, labels IGB##), meteorological stations from the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (circles, labels ILL#), and Check Dam 29 (CD29, square) where the flow depth and bedload impact rates of the study were observed. The location areas of two seismically detected rock avalanches (Rock 1 in red and Rock 2 in green) are shown.

Data quality

With the exception of twostations (IGB02 with power loss and IGB08 with water infiltration), all stations were operational during the entire experiment. The recorded seismic signals had sufficient quality, no undue disturbance from human activity (road traffic, hikers) and limited perturbations from rainfall, which allowed us to detect and analyse three debris flow events. They were all triggered in July, by convective storms. For the event on the 13th of July, the debris flow had a complex seismic signal showing several long duration pulses of high-frequency seismic energy that were observed only at side-channel sites (Fig. 2). In addition, many short duration signals were recorded at all stations. A comparison with independent rainfall data highlights a geomorphic origin of these seismic signals, coming from both hillslopes and channel. So far, we have focused our attentions on this specific debris flow event.

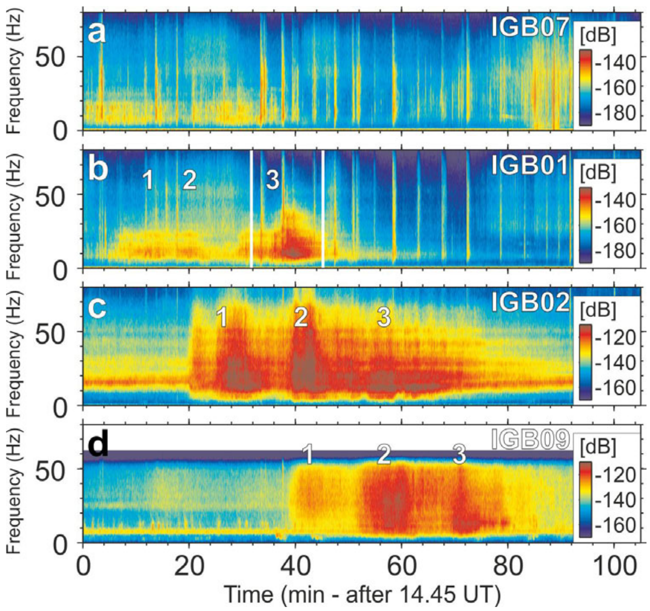

Figure 2: Seismic records of principal geomorphic activity in the Illgraben associated with rainfall on July 13, 2011. Spectrograms in decibel of the vertical seismic signal at stations IGB07 (a), IGB01 (b), IGB02 (c) and IGB09 (d). Note the downstream propagation of seismic energy pulses 1-3. Propagation velocities ranged from 1.0 to 4.5 m/s. Vertical white lines on (b) delimit the time span of Figure 3.

Processing and modelling

We performed a time-frequency analysis of the recorded seismic data at each site using a multi-taper approach. This procedure allows us to keep a correct frequency resolution for a limited number of points in the time series. Thus, we could maintain a high temporal resolution in the analysis of spectrograms and identify the main characteristics of the catchment activity. We manually checked the occurrence of high-frequency short time events assumed to be associated to hillslope processes. We located these events using a cross-correlation method of seismic envelopes in order to estimate the best delays of wave arrival at stations, because the identification of coherent seismic phases is difficult with geomorphic events. We then migrated the estimated time delays using a probability density approach with a ballistic propagation of seismic waves that takes into account the topography of the Illgraben catchment. The inferred seismic observations were finally compared with independent constraints, like meteorological conditions inside the Illgraben and *in situ* measurements of debris flow height and bedload impact rates at the outlet of the debris fan.

Interpretation and preliminary findings

During the 13 July 2011 debris flow sequence, stations along the channel recorded seismic activity with a broad high-frequency content ([1-50] Hz) that occurred in three main seismic energy pulses (Fig.2). Lasting about 10 minutes each, these pulses were timed progressively later at consecutive stations along the channel, showing the downstream propagation of their source. The third seismic pulse was preceded by a short duration signal with rock avalanche characteristics, which was recorded at most stations (Rock 1 at ~33 min, Fig.3). Applying our location approach, we found that this event occurred in the steep rock wall constituting the western flank of the catchment at an elevation of 1400-1900 m and within a 200×700 m area of uncertainty (Fig.1). The likely source area of this avalanche connected to the uppermost section of the Illgraben channel. After a delay of about 160 seconds, an increase of seismic energy was observed at station IGB01, making Rock 1 the probable trigger of flow pulse 3. During transit of flow pulse 3, a further significant, short duration event was detected at multiple stations (Rock 2 at ~37 min, Fig. 3.). This avalanche was located adjacent to the Illgraben channel, within a 400×750 m area of uncertainty, about 650 m downstream of station IGB01 (Fig.1). This mass wasting event may have been caused by ground vibrations or bank erosion during the passage of the sediment-laden flow pulse, and resulted in an immediate and sustained increase of 5% dB in the [9-12] Hz seismic energy recorded at station IGB01. We attribute this increase to a sudden addition of sediment into the flow.

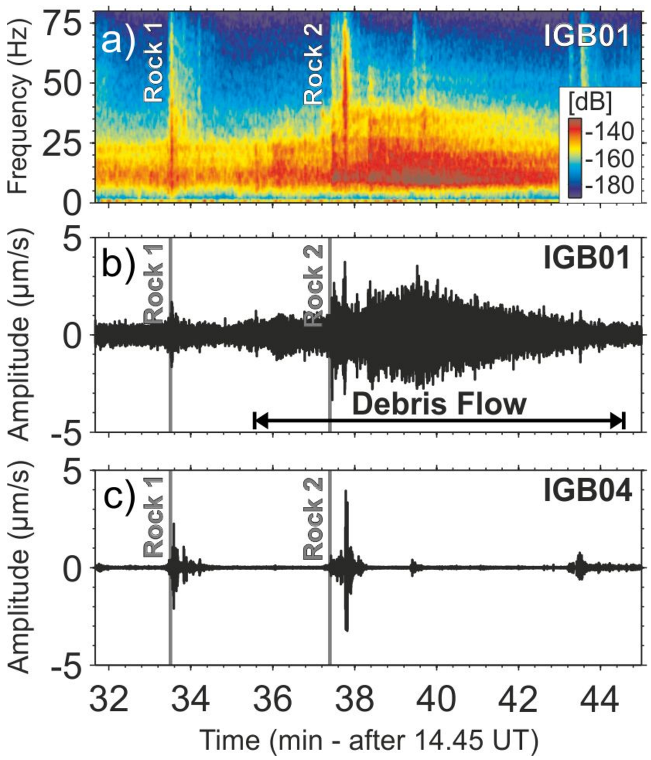

Figure 3: (a) Spectrogram of the vertical seismic signal at station IGB01 during the flow pulse 3. The seismic energy is given in decibel relative to the velocity. Two rock avalanches (Rock 1 and 2) caused a short, sharp increase of the seismic energy at high-frequency (>1 Hz). The gradual increase of the seismic energy over the time interval shown here reflects the increase of channel activity, and the approach and passage of a flow pulse. (b-c) Vertical [1-50] Hz bandpass filtered seismograms at stations IGB01 (b) and IGB04 (c). Note the absence of channel induced seismic signals at station IGB04 and the prominence of signals from rock avalanches 1 and 2 at both stations (gray lines).

The link between pulses of seismic energy recorded at stream-side stations and the flow propagation in the Illgraben channel can be used to infer some characteristics of the stream dynamics. Seismically determined flow velocities ranged from 1.0 to 4.5 m/s and are consistent with measured debris flow velocities in the channel (0.8-7 m/s) [Badoux et al., 2009]. The propagation velocity showed some spatial variations with lower values of ~ 1 m/s inside the catchment (between IGB01 and IGB02) than on the debris fan (~ 4 m/s, Fig.4a). Despite the similarities in flow velocity, the energy level of seismic signals developed between stations and differed between flow pulses. The seismic energy of all three flow pulses increased by 30-35% dB between IGB01 and IGB02, inside the Illgraben catchment. In contrast on the debris fan between IGB02 and IGB09, the energy decreased by 18% dB for flow pulse 1, and only by 5% dB for the flow pulses 2 and 3 (Fig.4b). These variations reflect a clear evolution of the flows down the channel, which could be linked to changes in the hydrodynamics of the flows but also the concentration of sediments (suspended load and bedload), affecting the flow rheology and their interactions with the channel bed.

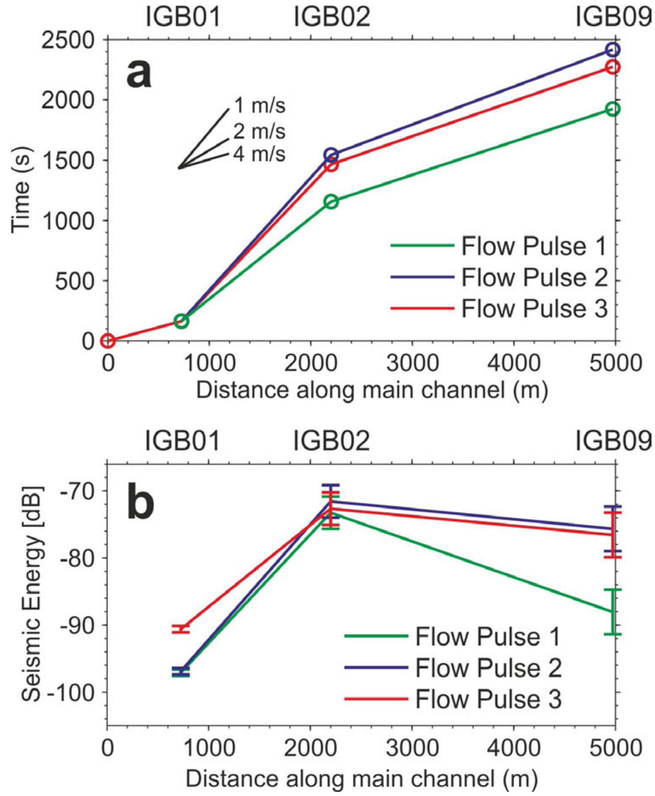

Figure 4: Velocity and energy characteristics of the debris flow sequence. (a) Downstream propagation of the three main flow pulses. The propagation is defined with the recordings of seismic envelopes at side-stream stations IGB01, IGB02 and IGB09. (b) Mean seismic energy of each flow pulse recorded at the same stations. The amplitude in decibel is corrected for the geometrical spreading of body waves.

A comparison of the recorded seismic signals of the flow pulses with data from *in situ* stream monitoring yields further information about the flow properties and their evolution. At station IGB09, flow pulse 1 had relatively little seismic energy below 15 Hz, whereas pulses 2 and 3 had more energy at lower frequencies and greater seismic amplitudes (Fig. 5). In contrast, the flow depth at CD29 was similar for pulses 1 and 2 (Fig. 5), and it peaked between pulses 2 and 3 when the seismic energy reached a temporary low (between 65 and 70 min, Fig. 5b). In addition, the flow depth of pulse 3 was relatively small, 45% below the peak value, whereas seismic amplitude increased by 130% for the same period. These comparisons indicate that there is no direct relation between seismic signals and the water level, and that other flow attributes might be involved. Flow pulse 1 had a relatively low bedload impact rate, 20 times less than flow pulse 2, even though these flow had similar depths and velocities. Meanwhile, the seismic amplitude increased by 215% at IGB09 from flow pulse 1 to flow pulse 2. Flow pulse 3 had a moderate seismic amplitude and bedload activity. Thus, the recorded seismic amplitudes are in qualitative agreement with bedload observations rather than with flow depth.

Thus, our seismic data suggests that an effective, two-way link exists between the Illgraben channel and the surrounding hillslopes, whereby mass wasting during rainstorms can cause the constitution of a flow capable of transporting significant amounts of sediment, and this flow in turn can induce further mass wasting during passage. In the Illgraben, seismically determined flow velocities indicate that the effects of channel roughness dominated over those of channel slope. Indeed, velocities were systematically lower inside the catchment where channel roughness is maximum. The seismic motoring of the debris flow propagation can also reveal the dynamics of channel processes, like the erosion, transfer and deposition of sediments. Finally, the flow rheology was qualitatively estimated (hyper-concentrated flow or debris flow).

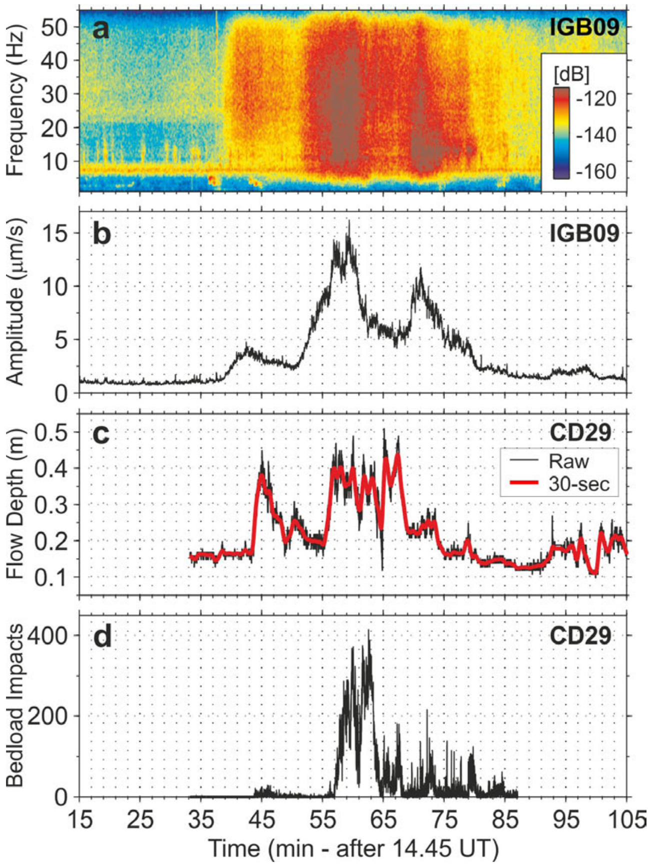

Figure 5: Flow pulse characteristics on the distal fan. (a) Spectrogram in decibel of the vertical seismic signal at station IGB09 during passage of flow pulses 1-3. (b) [5-50] Hz Vertical seismic envelop at IGB09 showing three flow pulses. (c) Raw (black line) and 30-sec smoothed (red line) flow height data recorded at CD29, 400 m downstream of IGB09 (2 minutes at established flow speed). (d) Bedload impact rates recorded at CD29.

Conclusions and recommendations

The deployment of a 2-D seismological network in small upland catchments allows a detailed survey of the acting surface processes. Geomorphic activity triggered by convective rainstorms can be mapped with a spatial resolution (hundreds of meters) that allows us to infer a two-way link between hillslope and channel processes. Such couplings are difficult to demonstrate with classical methods and can be studied in near real-time with seismology. We can now investigate their triggering mechanisms with respect to environmental conditions (precipitation, topography, lithology…). Further, characteristics of sediment-laden flows can be inferred from seismology, offering an opportunity to study channel dynamics and flow behaviour. And finally, seismic monitoring allows early identification of potentially destructive geomorphic events, well in advance of their registration by in situ monitoring, raising the prospect of improved debris flow warning systems.

Several aspects of this approach must now be further explored, constrained and tested. Open question include the best way to deal with complex velocity structures of high relief topography, the estimation of event magnitude from seismic records, and the identification of multiple, simultaneously active sources. To address these questions, and to pursue further geomorphic studies with this potentially powerful technique, we have acquired and deployed ten intermediate band seismometers in the Illgraben for a longer survey. Our experience with the NERC instruments was essential to our equipment selection and network configuration.

Publications

A manuscript with key findings on the 13 July 2011 storm event is currently being revised for publication:
Burtin, A., **Hovius, N.**, McArdell, B.W., Turowski, J.M. & Vergne, J.: Dynamic links between channel and hillslopes revealed by seismic monitoring. *Earth and Planetary Science Letters.*

A table of instrument deployment details

STATION	Latitude (°)	Longitude (°)	Elevation (m)	Sensor	First Day	Last Day
IGB01	46.27759	7.61520	1456	CMG-6TD	193/2011	271/2011
IGB02	46.28590	7.62761	0947	CMG-40T	175/2011	207/2011
IGB03	46.28291	7.64045	1649	CMG-6TD	182/2011	269/2011
IGB04	46.26428	7.62626	2203	CMG-6TD	183/2011	270/2011
IGB05	46.25774	7.61419	2500	CMG-6TD	182/2011	270/2011
IGB06	46.26692	7.60288	2165	CMG-6TD	183/2011	270/2011
IGB07	46.27511	7.59412	1973	CMG-6TD	183/2011	270/2011
IGB08	46.29733	7.61758	0748	LE3D-S	180/2011	200/2011
IGB09	46.30722	7.63289	0718	LE3D-S	180/2011	269/2011
IGB10	46.30368	7.64399	0736	LE3D-S	175/2011	269/2011

References

Badoux, A., Graf, C., Rhyner, J., Kuntner, R., McArdell, B.W., 2009: A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. Natural Hazards 49 (3), 517–539. doi:10.1007/s11069-008-9303-x

Berger C., B.W. McArdell, & F. Schlunegger, 2011: Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the time scales of debris flow activities. Geomorphology 125, 421-432

Brardinoni, F., Slaymaker, O. & Hassan, M.A., 2003: Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology, 54, 179-196

Burtin, A., L. Bollinger, J. Vergne, R. Cattin, & J.L. Nábelek 2008: Spectral analysis of seismic noise induced by rivers: A new tool to monitor spatiotemporal changes in stream hydrodynamics, J. Geophys. Res., 113, B05301, doi:10.1029/2007JB005034

Burtin, A., Vergne, J., Rivera, L., Dubernet, P.-P., 2010: Location of River Induced Seismic Signal from Noise Correlation Functions. Geophys. J. Int. 182 (3), 1161-1173

Burtin, A., Bollinger, L., Cattin, R., Vergne, J., Nábelek, J.L., 2009: Spatiotemporal sequence of Himalayan debris flow from analysis of high-frequency seismic noise. J. Geophys. Res. 114

Burtin, A., Cattin, R., Bollinger, L., Vergne, J., Steer, P., Robert, A., Findling, N. & Tiberi, C., 2011. Towards the hydrologic and bed load monitoring from high-frequency seismic noise in a braided river: the 'torrent de St Pierre', French Alps. J. Hydrol. 408(1-2), 43-53, doi:10.1016/j.jhydrol.2011.07.014

Helmstetter, A. & Garambois, S., 2010. Seismic monitoring of Séchilienne rockslide (French Alps): analysis of seismic signals and their correlation with rainfalls. J. Geophys. Res. 115, F03016, doi:10.1029/2009JF001532

Hsu, L., Finnegan, N. J. & Brodsky, E. E., 2011. A seismic signature of river bedload transport during storm events. Geophys. Res. Lett. 38, L13407, doi:10.1029/2011GL047759

Huang, C.-J., Yin, H.-Y., Chen, C.-Y., Yeh, C.-H. & Wang, C.-L., 2007: Ground vibrations produced by rock motions and debris flows. J. Geoph. Res. 112, doi:10.1029/2005JF000437

Lin, G.W., Chen, H., Hovius, N., Dadson, S., Meunier, P., and Lines, M., 2008: Effects of earthquake and cyclone sequencing on landsliding and fluvial sediment transfer in a mountain catchment. Earth Surf. Process. Landforms doi:10.1002/ESP1716

Malet, J.P., Maquaire, O. & Calais, E., 2002: The use of Global Positioning System techniques for the continuous monitoring of landslides: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France). Geomorphology 43, 33-54

Nábelek, J., G. Hetenyi, J. Vergne, S. Sapkota, B. Kafle, M. Jiang, H. Su, J. Chen, B.-S. Huang, & the Hi-CLIMB Team 2009: Underplating in the Himalaya-Tibet collision zone revealed by the Hi-CLIMB experiment, Science, 325, 1371-1374, doi:10.1126/science.1167719

Thomson, D. J. Spectrum estimation and harmonic analysis, Proc. IEEE, 70(9), 1055-1096 (1982)

Zhang, S., Hong, Y. & Yu, B., 2004: Detecting infrasound emission of debris flows for warning purposes. Proc. 10th Congress INTERPRAEVENT 2004, Z/359-Z/364