

Field Calibration of the Swiss Plate Geophone System at the Albula Stream and Comparison with Controlled Flume Experiments

Tobias Nicollier, Swiss Federal Research Institute WSL, Switzerland,
tobias.nicollier@wsl.ch

Dieter Rickenmann, Dr., Swiss Federal Research Institute WSL, Switzerland,
dieter.rickenmann@wsl.ch

Arnd Hartlieb, Dr., Oberrach Research Institute, Technical University of Munich,
Germany, arnd.hartlieb@tum.de

Introduction

The Swiss plate geophone (SPG) system is a bedload surrogate monitoring technique that has been calibrated in several mountain streams to quantify bedload transport (Rickenmann, 2017). The amplitude of the signal recorded by the SPG contains information about the grain-size distribution of the transported bedload. However, determination of bedload transport with the impact plate system ideally requires calibration with direct bedload sampling in the field. At the Albula stream in Switzerland, bedload samples were collected with a large net attached to a steel-frame and operated from a crane. These measurements were compared with the signal of the impact plate geophone system to convert the signal information into bedload transport rates. In addition, a set of controlled real scale experiments was performed at the outdoor flume facility of the Oskar von Miller institute in Germany. The reconstruction of the field conditions met at the Albula stream enabled to investigate various individual aspects influencing the measurement accuracy of the Swiss plate geophone system.

This study is the first step of a project that aims to investigate more in depth various individual aspects influencing the measurement accuracy of the Swiss plate geophone at different field sites, starting with the Albula stream. The objectives of this contribution are: (i) to briefly introduce the Swiss plate geophone system and the amplitude histogram method used to estimate the bedload flux for different grain size classes; (ii) to present the field calibration measurements conducted at the Albula field site; (iii) to describe the controlled flume experiments; and finally (iv) to discuss some results from both sets of calibration measurements and potential errors emerging during their interpretation.

The Swiss plate geophone system

Indirect impact measuring systems have been intensively used and developed over the last decade to estimate bedload transport in mountain streams. They have the advantage of providing continuous records of the transport activity both in time and over a cross-section. One of them, the Swiss plate geophone system, has been successfully deployed to quantify bedload transport intensity in several steep streams mainly in Switzerland and Austria (Rickenmann, 2017; Wyss et al., 2016a, b, c). The system consists of geophones fixed under a series of steel plates of standard dimensions embedded along the transect of a stream. While the Japanese pipe microphone (hydrophone) (Mizuayama et al., 2010a, b) and the hydrophone (Geay et al., 2017) both record an acoustic signal generated by an impact on a structure or between the grains, the SPG system records a seismic signal, i.e. vibrations of an elastic medium, generated when bedload particles slide, roll or saltate over a steel plate. The current induced by the geophones is proportional to their vibration velocity (Rickenmann et al., 2014).

Wyss et al. (2016a) developed a method to derive the transport rate as a function of the grain size based on the amplitude of the seismic signal, the amplitude histogram (AH) method. This method relies on the assumption that the amplitude (in Volts) of the seismic signal correlates with the size of the impacting grains. Seven amplitude classes j were defined, each corresponding to a defined grain size fraction and amplitude-thresholds. Whenever the signal exceeds one of these thresholds, an impulse is recorded and the summed impulse counts IMP_j are stored for a given time interval and for a given amplitude class j .

Assuming that the number of impulses is related to the number of transported particles, a calibration coefficient α was defined for every amplitude class j so that:

$$\alpha_{imp_i,j} = \frac{IMP_{i,j}}{N_{i,j}} \quad (1)$$

Where $IMP_{i,j}$ is the number of impulses registered for an amplitude class j for a bedload sample i , and $N_{i,j}$ is the number of particles constituting the different fractions (s. also Wyss et al., 2016a; Rickenmann et al., 2018). The number of particles per grain-size class is determined with a power law relation between the mean weight and the mean diameter for each grain-size class, which was empirically determined for bedload particles sampled at the Albula stream.

Calibration measurements by direct bedload sampling at the Swiss Erlenbach stream were necessary to develop the AH method, i.e. to empirically determine the $\alpha_{imp_i,j}$ values. This method has recently been slightly improved for the interpretation of the Erlenbach geophone data, based on an extended number of direct bedload measurements (Rickenmann et al., 2018). In addition, it was shown that controlled laboratory flume experiments are important for a better understanding of the factors influencing the calibration of these measuring methods (Wyss et al., 2016 b, c).

Calibration measurements at the Albula field site

In 2015 a new bedload transport monitoring station was put into operation at the Albula stream in Switzerland. The measuring station is located in the village of Tiefencastel in the Eastern part of the Swiss Alps, at 856 m above sea level, and where the catchment area is 529 km². The hydrologic snow melt regime is characterized by low flow in winter and peak flows between late April and early July. At the measuring site, a Swiss plate geophone system is installed, including a total of 30 steel plates embedded into a 15 m wide concrete sill; every second steel plate is equipped with either a geophone or an accelerometer sensor (Rickenmann et al., 2017). A preliminary analysis after one season of measurements showed a fairly good correlation between discharge and impulses recorded by both types of sensors. Also, a rough estimation of the linear calibration coefficient k_b [kg^{-1}] was made, which can be derived from the total number of recorded impulses IMP_G with the geophone sensors and the mass M [kg] of bedload transported over the plates (Rickenmann et al., 2017):

$$IMP_G = k_b M \quad (2)$$

The linear calibration coefficient k_b typically ranges between 2 and 60 kg^{-1} and was found to depend on site-specific parameters, e.g. the mean water flow velocity (Rickenmann et al. 2014).

To further investigate the variability of the SPG signal response between different field sites, and also to calibrate the SPG system at the Albula stream, a field measuring campaign was carried out during the snow melt period in Spring 2018. Direct bedload measurements were made with a net sampler, a development and adaptation of a bedload trap developed by Bunte and Abt (2003). Similar bedload measurements with a net sampler had been previously made in mountain streams in Austria (Kreisler et al., 2017) and in Northern Italy (Vignoli et al., 2016). The sampling device consists of a steel frame, a sampler bag and steel

bar (Figure 1). The 3 m long sampler bag is made of a polyethylene net and has a mesh size of $8 \text{ mm} \times 8 \text{ mm}$, what corresponds to the size of the smallest particle size that can be sampled. The frame on which the net is fixed has an opening size of 500 mm width and 300 mm height in order to cover the whole width of a steel plate. In addition a thin tilted metal plate was welded at the bottom pipe of the intake to ensure a good coupling with the concrete sill. The steel bar mounted centrally on the upper part of the intake frame is connected to a crane over a hydraulic rotator. This system enables to compensate for fluvial forces and place the aperture of the frame perfectly parallel to the steel plate. Three additional elements were necessary to ensure a correct bedload sampling. (i) First, a cable with markers on it was stretched from one bank to the other to indicate the correct position of the sensor plates. (ii) Second, two static ropes attached on each side of the frame and handled from the banks gave support to the hydraulic rotator to correct for fluvial forces at high discharges. (iii) Finally, an aluminum tube was fixed horizontally at the top of the steel bar to facilitate the positioning of the frame parallel to the sensor plates in turbid water. Between bedload measurements the flow velocity was recorded at different depths with an electromagnetic flow meter fixed on the steel frame.

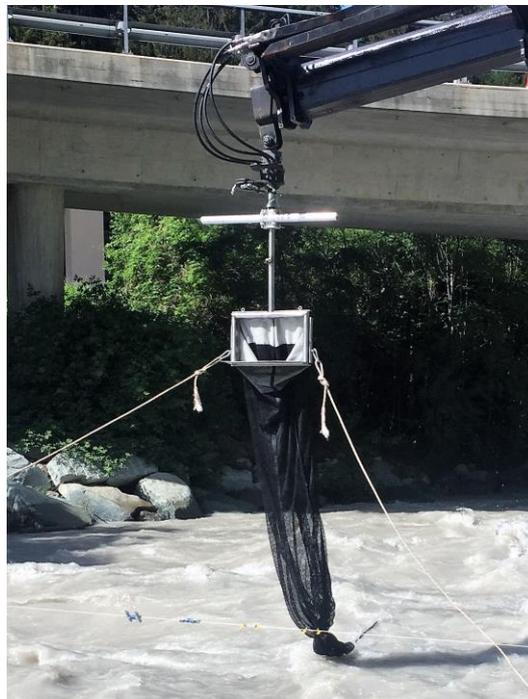


Figure 1. The net sampler used for the calibration measurements at the Albula field site

At all sites equipped with the SPG system, the geophone signal is sampled at a rate of 10 kHz. During normal monitoring conditions (i.e. when no calibration measurements are conducted), a pre-processing of the geophone signal provides summary values (e.g. summed number of impulses recorded within one minute). Due to data storage limitations, the raw signal is not recorded continuously, but only during periods of transport activity. For the relatively short durations of the calibration measurements, the raw seismic signal is recorded.

A calibration measurement starts as soon as the steel frame is placed on the riverbed immediately downstream of a selected sensor plate. The duration of each bedload sampling period had to be carefully controlled for any given discharge and bedload transport activity, to avoid overloading the sampling bag. During the first part of the campaign, at the beginning of May, the estimated discharge ranged between 30 and 40 m^3/s . Measures with an electromagnetic flow meter fixed on the crane showed velocities up to 1.70 m/s around 10 cm over the riverbed. During the second part of the campaign, at the end of May, the discharge

ranged from 45 to 60 m³/s with flow velocities of up to 2 m/s around 10 cm over the riverbed. In total sixty-two bedload samples with masses M ranging from 5 kg to 500 kg were collected over time intervals lasting between 1 and 10 minutes.

This bedload sampling technique proved to be an efficient solution for the calibration measurements conducted at the Albula field site. First, the relatively large capacity of the net allowed to collect bedload samples with a large range of masses. Secondly, having the sampling system fixed on a mobile crane allowed to collect samples at various locations and under different flow conditions within a short time interval; the flow velocity at locations closer to the bank was smaller than in the center of the stream.

Controlled full scale experiments

In addition to the calibration measurements at the field site, controlled real scale experiments were performed at the outdoor flume facility of the Oskar von Miller institute in Germany. The main purpose was to replicate the bed and flow conditions of the Albula field site, i.e. to have a similar channel slope and bed roughness, and to apply similar unit discharges as during the field calibration measurements resulting in similar flow velocities. This set-up then allows investigating changes in the instrument response when variables such as the grain size, discharge and transport rate are being modified.

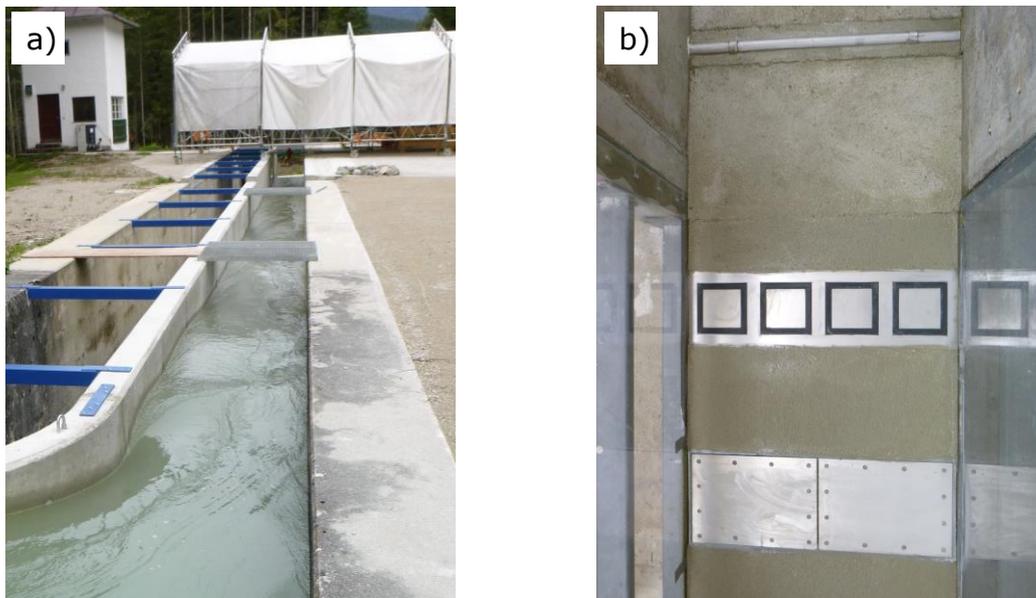


Figure 2. a) Downstream view of the 24 m long flume test section, and b) View of the measuring cross-section with the two steel plates of the SPG system (bottom) and the four smaller steel plates of the so-called Miniplate Accelerometer system (middle) and the Japanese pipe (top) .

The test reach consists of a 24 m long, 1.02 m wide and max. 2.02 m deep concrete flume (Figure 2a). The channel has a slope of 0.7 % and is divided in several subsections. In the first section, the bed of the flume has been paved with pebbles of approximately the D_{67} and the D_{84} sizes of the surface bed material in the Albula stream, reproducing the roughness measured in the field. The relatively large space between the pebbles helps to avoid the retention of bedload particles fed into the flume during the tests. Downstream of that is a short section imitating the concrete sill with large blocks in the field. At the measuring cross-section three different indirect bedload monitoring instruments are embedded: two steel plates with geophones, four smaller steel plates with accelerometers, and a Japanese pipe microphone (Figure 2b). Parts of the concrete wall on each side of the SPG system and the accelerometers were replaced by a Plexiglas window enabling to record the particle transport over the steel plates with a video camera. The most downstream section of the flume is made

of pure concrete ending with an overfall into a large retention basin. The flow conditions at the test site can be adjusted precisely with the help of a series of long intake basins separated from each other by sluice gates. The flume at the test site has a maximum discharge capacity of 2.7 m³/s what enables to reach a flow velocity of about 2.5 m/s at a vertical distance of 10 cm above the geophone plates.

Two types of experiments were performed. The single grain size experiments were run with a fixed mass or number of grains of each of the seven defined classes mentioned earlier (see previous section titled "Swiss plate geophone system"). This first type of experiment should provide information on the close linkage between the instrument response, the grain size and the flow conditions. In a second stage, grain mixtures reflecting the natural grain size distributions measured at the Albula stream were used. Here the goal was to investigate whether it is possible to reproduce the seismic datasets recorded in the field by imitating the natural flow and transport conditions in the flume. For that purpose sieved bedload material originating from the calibration measurements described in the previous section titled "Calibration measurements at the Albula field site" was used. Each grain, with a b-axis ranging from 10 to 140 cm, was colored depending on the particle-size class to facilitate the later sorting.

In total around 450 runs were performed. Each run consisted of the following main steps. (i) First, depending on their class, grains were fed into the channel either directly on the bed through a vertical plastic pipe, or at the surface using a tiltable basket. Particles were fed into the flow about 8 m upstream from the impact sensors. (ii) Simultaneously, the recording of the raw geophone signal and the video were started. (iii) As soon as all the grains had passed the sensors, which could easily be controlled visually due to the limited turbidity of the water, both recordings were stopped. (iv) Finally, after completion of several test runs, the sluice gates were closed, the grains collected from the retention basin and sorted by size.

Results and Discussion

This section presents a brief comparison between the field and the controlled flume experiment data to address the last but most essential question.

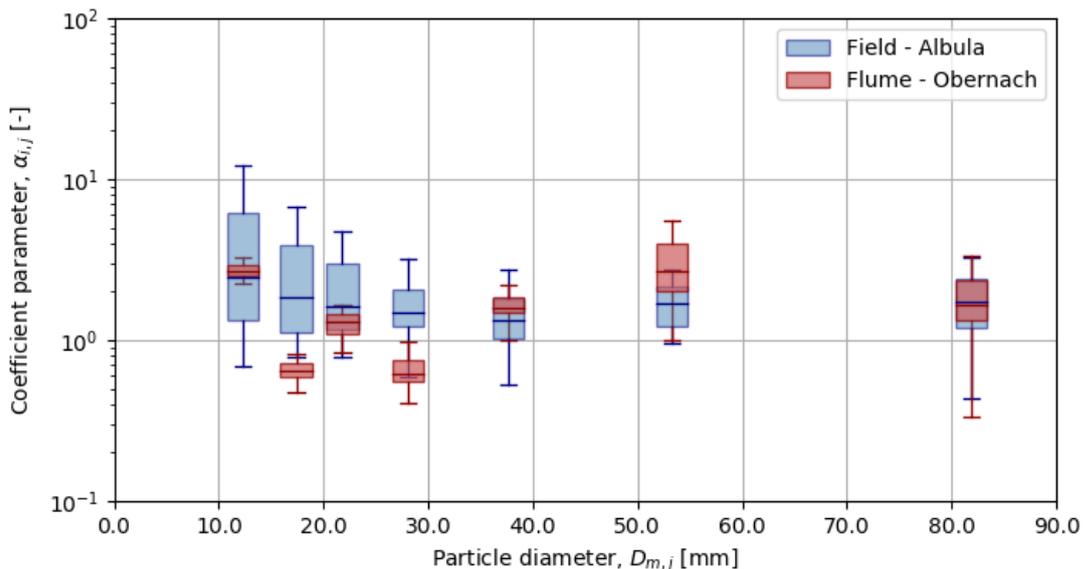


Figure 3. The α coefficient as a function of the geometric mean grain size of each amplitude class j for the calibration measurements at the Albula field site (red) and the outdoor flume facility (blue)

While the single grain class experiments only reproduce individual components of the real bedload transport of the Albula, the second set of experiments, based on particle mixtures, used a similar grain size distribution (GSD) as measured in the field and can therefore be directly compared with the field data. Figure 3 shows the $\alpha_{i,j}$ coefficient of each calibration measurement i conducted at the Albula stream and the outdoor flume facility at water flow velocities of around 2 m/s at a height of 10 cm above the sensor plates. The coefficient $\alpha_{i,j}$ is plotted as a function of the geometric mean particle size $D_{m,j}$ of each amplitude class j (see previous section titled "Swiss plate geophone system").

One can notice the generally reduced scatter of the flume data as compared to the field data (Fig. 3). This is not unexpected since the flow conditions in the flume and the GSD of the particle mixtures were almost the same for each run. On the other hand, the presented field data were collected over two days, and both flow conditions and transport rates and GSD are expected to have been more variable than in the flume. Only the $\alpha_{i,j}$ coefficients of the second and the fourth amplitude classes show clearly lower values on average than in the field. This could be due to a previously uninvestigated aspect of the Swiss plate geophone system, namely the recording of apparent impulses generated by impacts of (larger) particles on a neighboring. In fact, the seismic signal generated by an impact can propagate through the whole metallic structure and can be recorded by other geophones as an additional impulse, mostly in the lower amplitude classes because of signal attenuation. Lateral transmission of the seismic signal would therefore have a smaller impact in the flume experiments, with only two sensor plates, than at the field site where thirty plates are embedded. The high value of the $\alpha_{imp_i,j}$ coefficient of the smallest amplitude class recorded during the flume experiments was found to be caused by the particles impacting on the concrete bed in the vicinity of the sensor plates. The good correlation between both datasets for this amplitude class therefore needs to be considered with caution. For the larger amplitude classes, a very similar instrument response can be observed for the flume experiments and at the Albula stream field measurements, which is a promising result.

Concluding remarks

This preliminary analysis showed that the presented flume experiment setup allows a realistic reproduction of the flow and bedload transport behavior as observed at the Albula field site, resulting in a similar signal response of the SPG system for both data sets. The analysis also suggests that controlled experiments may help to refine the interpretation of calibration measurements made in the field. A more detailed analysis of the collected datasets, in particular of the video recordings of each run, is expected to provide further insights into the interpretation of the seismic signal registered by the SPG system.

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