

# Improving bedload transport determination by grain-size fraction using the Swiss plate geophone recordings at the Erlenbach stream

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**Abstract.** Direct bedload samples were taken with a large metal basket at the steep Erlenbach stream in Switzerland. These measurements were compared with the signal of the Swiss impact plate geophone system to derive information about bedload transport. The so-called amplitude histogram (AH) method was developed in an earlier study to estimate the bedload flux for different grain-size classes at the Erlenbach. A new analysis of a larger set of measurements was made here to improve the performance of the AH method. The approach relies on an identification of the transported grain sizes through their dependency on the signal amplitude. As a new element we introduce here the impulse rate, which is found to affect the number of impulses recorded for each amplitude class. As compared to the original method, the new version of the AH method shows a slightly improved performance for total calculated bedload mass, and results in a clearly better agreement between calculated and measured characteristic grain sizes.

## 1. Introduction

Several surrogate measuring techniques have been successfully calibrated to determine total bedload flux [1]. Typical examples of surrogate measuring techniques are the Swiss impact plate geophone system [2] and the Japanese pipe microphone system [3]. Essentially, linear or power law relations were established between a simple metric characterizing the acoustic signal (such as impulse counts) and bedload mass, typically based on contemporary direct bedload transport measurements in the field [e.g. 2, 3, 4, 5]. Ideally, a surrogate bedload transport measuring technique should not only be calibrated for total mass flux but should also allow for a conversion of the acoustic signal into bedload transport rates for different grain-size classes. Such a procedure was developed for the Swiss plate geophone (SPG) measurements at the Erlenbach stream, for which an amplitude-based classification of the signal packets was successful in distinguishing seven grain-size classes with median diameters ranging from 12.3 mm to 83 mm [6]. A somewhat similar method was proposed for the Japanese pipe microphone system, by analysing the pulses recorded with different channels, corresponding to different amplification levels, and thus predicting bedload transport and grain size fraction for median diameters ranging from 9 mm to 36 mm for

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flume data. However, when applying the predictive relations to field data, the agreement with observed bedload transport and particularly with observed median grain sizes larger than about 30 mm was much poorer [4]. This approach is in fact analogous to the “packet” counts for different amplitude classes with the SPG system described in [6].

The purpose of the present contribution is to introduce a refined analysis of the bedload transport measurements with bedload samples and the SPG data from the Erlenbach stream, which resulted in an improved version of the original amplitude histogram (AH) method [6]. The revised method was developed to improve the prediction of the grain-size distribution based on the SPG measurements.

## **2. Field site, measurements and original AH method**

### **2.1. Field site and measurements**

In the Erlenbach stream, a pre-alpine steep channel in Switzerland, sediment transport has been monitored for more than 30 years. A sediment retention basin at the catchment outlet is surveyed at regular intervals and after large flood events. Bedload transport has been continuously monitored with the SPG system since 2000. In 2009, the measuring station was enhanced by installing an automatic system to obtain bedload samples. Movable metal baskets are mounted on a rail at the downstream wall of the large check dam above the retention basin, and they are moved automatically into the flow to take bedload transport samples [7].

The SPG system consists essentially of a steel plate equipped with a geophone sensor underneath and mounted flush with the streambed. The steel plates at the Erlenbach have dimensions of  $L \times W \times T = 36 \text{ cm} \times 49.7 \text{ cm} \times 1.5 \text{ cm}$ , where  $L$  is the downstream length,  $W$  the transversal width, and  $T$  the thickness of the steel plate. A 20DX geophone from Geospace Technologies (Houston, Texas) in a PC801 LPC Land-case is fixed to the steel plate, inside an aluminium case. Moving bedload particles cause impact shocks which are transmitted by the plate to the geophone sensor. The sensor has a magnet in a coil as inductive element. The magnet moves with the steel plate and induces a current in the coil which is proportional to the velocity of the magnet or the velocity of the displacement of the plate [7].

From 2009 to 2017 more than 100 bedload samples were taken with the moving basket. Simultaneously, the full raw signal of the SPG system was recorded during the basket sampling. For the analysis, the geophone measurements of the two central plates (GP07 and GP08) were used, which cover a width of 1 m upstream of the basket that collects bedload over the same stream width of 1m, for all grain sizes larger than 10 mm. A total of 88 bedload samples were used in this analysis, with bedload masses ranging from 9 kg to 382 kg. Samples with small masses and very short sampling durations were excluded. During the bedload sampling the raw signal of the SPG measurements was recorded with a sampling rate of 10 kHz.

### **2.2. Original AH method**

Information about the grain-size distribution of the transported bedload over the Swiss geophone plates can be determined using the number of impulses per amplitude class (called amplitude histogram method). Amplitude histogram data can be interpreted as a statistical distribution of the signal’s amplitude over the time intervals with particle impacts on a plate. Using the number of bedload particles per unit mass (determined from the basket

measurements), absolute bedload masses for each grain-size class were calculated for the Erlenbach stream with the original AH method [6], which is summarized below. From a total of 46 bedload samples (period 2009 – 2012), 31 were used for the calibration of the method and 15 for the verification. For  $j$  grain-size classes an amplitude threshold value  $A$  in (V) (upper class boundary value) corresponds to a threshold particle size  $D$  in (mm) separating the grain-size class (Wyss et al. 2016a). An empirical relation was determined between (maximum) grain size  $D$  in (mm) and (maximum) signal amplitude  $A$  in (V) used in [6], based on the 31 calibration bedload samples:

$$D = 89.5 A^{0.585} \tag{1}$$

It was assumed that the number of impulses per amplitude class,  $IMP_j$ , are related to the number of particles in the corresponding grain-size class,  $N_j$ , with a mean weight,  $G_{mj}$ , by a coefficient  $\alpha_j$  determined from the bedload samples, as follows:

$$IMP_j = \alpha_j N_j \tag{2}$$

The analysis resulted in the following empirical power law relation between  $\alpha_j$  and the geometric mean diameter  $D_{mj}$  in (mm) per class, where the median value of  $\alpha_j$  of the 31 bedload samples was used to determine the empirical relation:

$$\alpha_j = 0.0093 D_{mj}^{1.09} \tag{3}$$

where the coefficient 0.0093 has the units ( $\text{mm}^{-1.09}$ ), and  $j$  is the index for the grain-size class. To estimate the bedload mass per grain-size class,  $M_{cal,j}$ , the following relation was used:

$$M_{cal,j} = G_{mj} N_j = G_{mj} IMP_j / \alpha_j \tag{4}$$

To determine the mean weight,  $G_{mj}$  in (g) for each grain-size class with  $D_{mj}$  in (mm), the following empirical relation reported in [6] was used:

$$G_{mj} = 0.00219 D_{mj}^{2.88} \tag{5}$$

So  $\alpha_j$  is essentially a (average) dimensionless number to convert the number of impulses ( $IMP$ ) to the number of grains that passed over the plate for each grain-size class (detected and undetected). It is noted that for the development of the original AH method seven grain-size classes were used (with  $D_{mj}$  values of 12.3, 17.4, 21.8, 28.1, 37.6, 53.2, and 83.0 mm).

### 3. Development of new AH method and results

As a first step for the development of the new AH method we repeated the analysis described in section 2.2 using 88 bedload samples from the Erlenbach field site. We slightly redefined the seven grain-size classes (with  $D_{mj}$  values given in the last row of Table 1) to determine the number of grains per class for each bedload sample, and to estimate from these the median  $\alpha_j$  values based on the  $IMP_j$  values for each class. This resulted in an equation very similar to (3), confirming the compatibility of the two procedures. The lowest class no. 1 for the AH data in Table 1 has a lower threshold amplitude of  $A = 0.028$  V, which corresponds to a grain size of  $D = 11.1$  mm according to eq. (1). Therefore, in this new analysis we truncated all the bedload samples at this lower threshold and considered only grains with  $D > 11.1$  mm. At many field sites equipped with the SPG system, the AH data is continuously being recorded for 18 amplitude classes, corresponding to 18 grain-

size classes; for the further development of the new AH method, we therefore used these 18 grain-size classes (Table 1).

A recent analysis of the SPG measurements from two Austrian mountains streams showed that for one of these (Fischbach) the conversion of the impulse rate *IMPT* into a unit bedload transport rate  $q_b$  was different for two different ranges of *IMPT* values [8]. This finding is in qualitative agreement with flume experiments that showed the SPG signal response to vary with grain size for a given unit bedload mass transported over the plate, with a peak value for intermediate grain sizes [9]. Because grain sizes tend to coarsen with increasing  $q_b$ , this effect is also present for changing *IMPT* values [8]. Therefore we examined the  $\alpha_j$  values (for the 88 bedload samples) as a function of the impulse rates *IMPT* for the seven grain-size classes, as given in row 8 in Table 1. We found trends for empirical power law relations of the form:

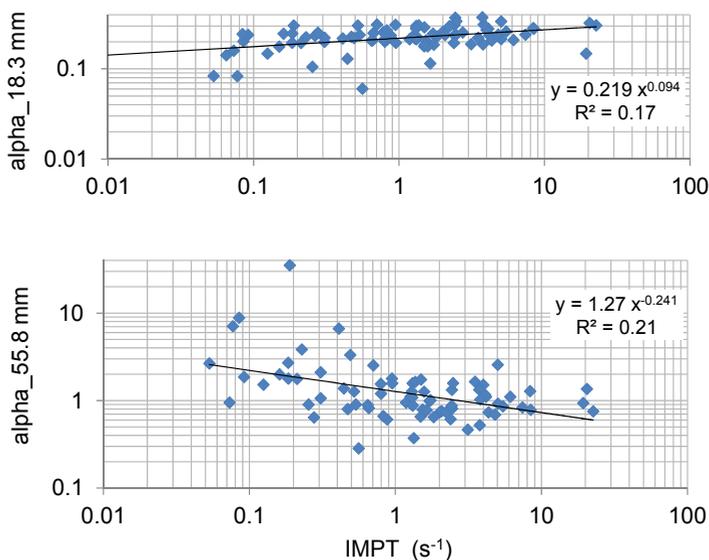
$$\alpha_j = b_j IMPT^{e_j} \tag{6}$$

where the *IMPT* values were determined for the geophone plate GP08 and for  $A > 0.079$  V. In total the geophone sensor GP08 recorded 92% of the summed impulses for GP08 and GP07 (for  $A > 0.079$  V), and thus 92% of the number of grains in the basket samples were assigned to GP08 for the regression analyses of eq. (6). Although the correlation coefficients R were generally rather low (see two example relations in Fig. 1), there was a systematic trend for the exponent  $e_j$  to be positive for the  $D_{mj}$  values smaller than about 30 mm and to be negative for the  $D_{mj}$  values larger than about 30 mm, as is indicated in rows 6 and 8 of Table 1.

**Table 1.** Characteristic values of the 18 AH classes, which are continuously recorded at several SPG sites, and which are used here in the development of the new AH method. The rows 5 and 6 indicate the values of the coefficient  $b_j$  and exponent  $e_j$  for each amplitude (and grain size) class; as compared to the regression equations (6), the values of  $b_j$  were adjusted here for the new AH method.

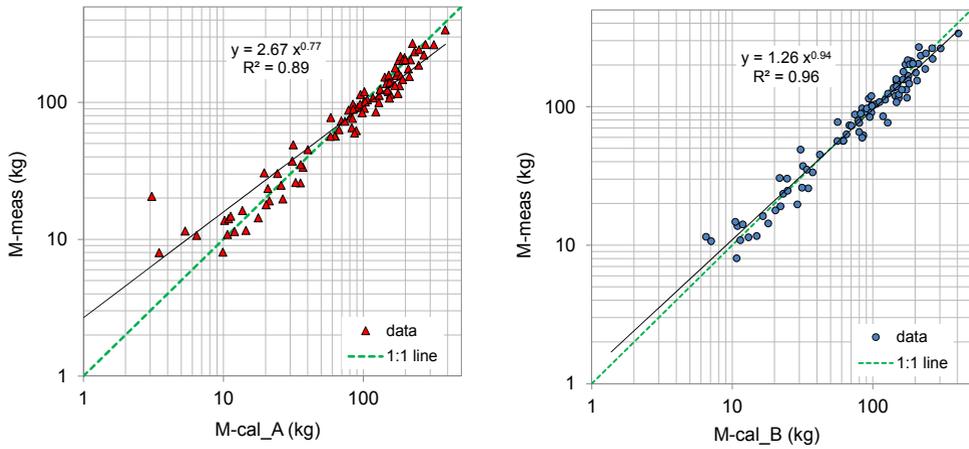
Class no. for AH data	1	2	3	4	5	6	7	8	9
Upper limit, amplitude A (V)	0.040	0.056	0.079	0.112	0.158	0.224	0.316	0.447	0.631
Upper limit, grain size D (mm)	13.6	16.6	20.3	24.9	30.4	37.3	45.6	55.9	68.4
Class mean grain size $D_{mj}$ (mm)	12.3	15.0	18.3	22.5	27.5	33.7	41.3	50.5	61.8
Coefficient $b_j$ (adjusted)	0.161	0.161	0.219	0.279	0.352	0.447	0.6	0.75	0.95
Exponent $e_j$ (from regression)	0.087	0.087	0.094	0.085	0.070	-0.055	-0.055	-0.238	-0.238
Class no. for basket sample analysis	1	2	3	4	5	6			
Regressions for eq. (6): $D_{mj}$ (mm)	13.6	18.3	22.5	27.5	37.2	55.8			

Class no. for AH data	10	11	12	13	14	15	16	17	18
Upper limit, amplitude A (V)	0.891	1.26	1.78	2.51	3.55	5.01	7.08	10	12
Upper limit, grain size D (mm)	83.7	102	125	153	188	230	281	344	383
Class mean grain size $D_{mj}$ (mm)	75.6	92.6	113	139	170	208	254	311	363
Coefficient $b_j$ (adjusted)	1.2	1.5	1.75	2	2.4	2.8	3.2	3.6	4
Exponent $e_j$ (from regression)	-0.164	-0.164	-0.164	-0.164	-0.164	-0.164	-0.164	-0.164	-0.164
Class no. for basket sample analysis	7								
Regressions for eq. (6): $D_{mj}$ (mm)	84.7								

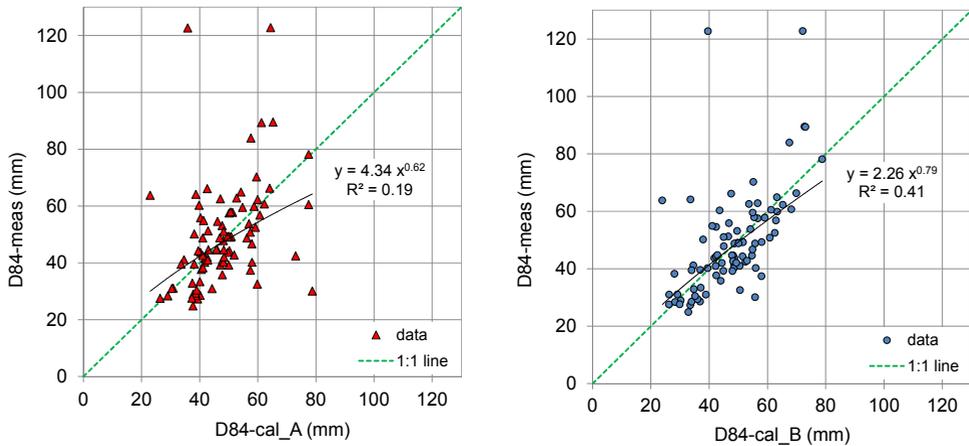


**Fig. 1.** Erlenbach: Empirical relations for the (dimensionless)  $\alpha_j$  values as a function of the impulse rates  $IMPT$  (determined for GP08 and  $A > 0.079$  V). Two example relations are shown for the classes with mean grain sizes of  $D_{mj} = 18.3$  mm (upper panel) and  $D_{mj} = 55.8$  mm (lower panel).

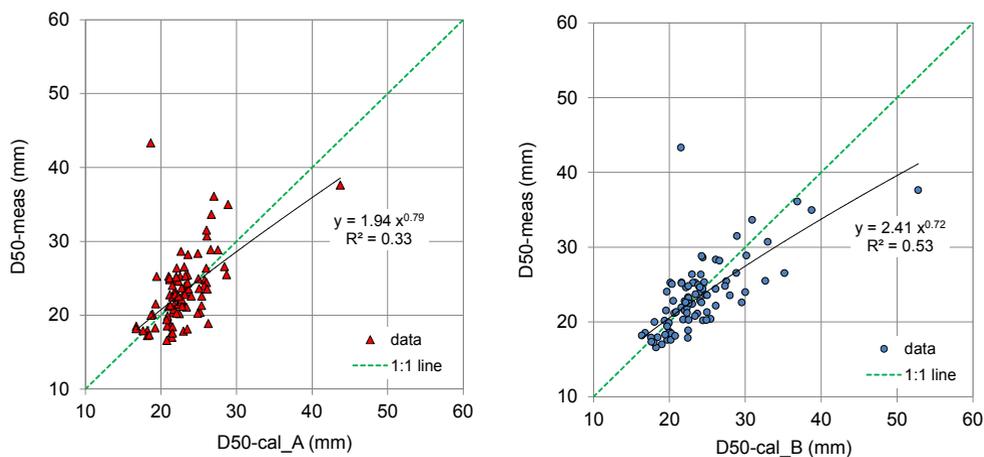
In the final part of the new analysis, the values of  $b_j$  and  $e_j$  obtained from the power law regressions of  $\alpha_j$  versus  $IMPT$  for the seven grain-size classes (last row of Table 1) were first directly used for each nearest (in terms of  $D_{mj}$ ) of the 18 grain-size classes of Table 1 (that are routinely recorded at several SPG sites). Using these regression values of both  $b_j$  and  $e_j$  resulted already in a clear improvement of the calculated total bedload masses  $M$  and of the characteristic grain sizes  $D_{84}$ ,  $D_{75}$ , and  $D_{50}$ , compared to the results of the original AH method. We could slightly further improve the new AH method by adjusting the coefficients  $b_j$  of eq. (6) by trial and error, but by keeping the exponents  $e_j$  as obtained from the regression analysis (final values are given in Table 1). This resulted in a further improvement of the calculated values  $M$ ,  $D_{84}$ ,  $D_{75}$ , and  $D_{50}$ , as compared to the measured values and illustrated in Figures 2, 3, and 4. In the figures, the original and the new AH method are referred to with the capital letters A and B, respectively. Using the adjusted coefficients  $b_j$  (as given in Table 1), the median values of  $\alpha_j$  of all 88 samples showed a smoother change (increase) with  $D_{mj}$  than when using the regression coefficients  $b_j$ . Thus the median values of  $\alpha_j$  were more similar to those given by eq. (3) of the original AH method.



**Fig. 2.** Erlenbach: Comparison of total bedload mass measured (M-meas) with the basket sampler (for  $D > 11.1$  mm) and calculated with the AH method (M-cal), using the original version (A, left panel) and modified version (B, right panel). The power law regression equations of measured versus calculated values and the 1:1 line help to assess the performance of the two methods.



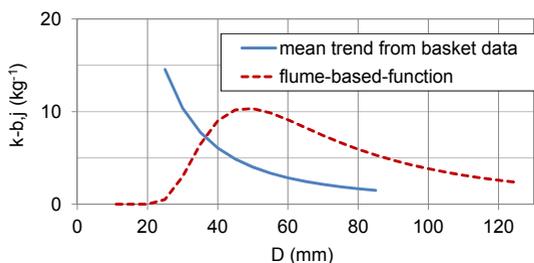
**Fig. 3.** Erlenbach: Comparison of the characteristic transported grain size  $D_{84}$  measured (D84-meas) with the basket sampler (for  $D > 11.1$  mm) and calculated with the AH method (D84-cal), using the original version (A, left panel) and modified version (B, right panel). The power law regression equations of measured versus calculated values and the 1:1 line help to assess the performance of the two methods.



**Fig. 4.** Erlenbach: Comparison of the characteristic transported grain size  $D_{50}$  measured (D50-meas) with the basket sampler (for  $D > 11.1$  mm) and calculated with the AH method (D50-cal), using the original version (A, left panel) and modified version (B, right panel). The power law regression equations of measured versus calculated values and the 1:1 line help to assess the performance of the two methods.

### 4. Discussion

In earlier studies with the SPG system the signal response  $k_{bj}$  has been defined as the number of impulses per unit bedload mass for a given grain size class [2, 9]. Using the AH data analysed for this study, the signal response  $k_{bj}$  was calculated for the seven grain size classes used for the basket sample analysis (Table 1). Then a mean trend line was determined based on the 88 bedload samples used in this study. It is compared in Fig. 5 with a curve for  $k_{bj}$  as a function of grain size  $D$  derived from flume experiments reported in [9].



**Fig. 5.** The signal response per unit bedload mass,  $k_{bj}$ , calculated from the basket measurements and the AH data (blue line), is compared to the signal response as determined from flume experiments (dashed red line) using bedload particles from the Erlenbach for different grain size classes (the flume based function is taken from Wyss et al. 2016 [9], for a mean flow velocity of  $3.5 \text{ m s}^{-1}$ ).

For grain sizes  $D$  larger than about 50 mm the curves show a qualitatively similar trend, although there is a difference (shift) in  $k_{bj}$  values of around a factor of 2 to 3. For grain sizes  $D$  smaller than about 40 mm the two curves in Fig. 5 show qualitatively opposing trends.

Contrary to the AH data from the field samples, in the analysis of the flume experiments all impulses produced by particles of a given grain size class were attributed to this same class. Thus for the field data and the AH analysis the smaller grain size classes include many impulses from the decaying signal oscillations caused by larger grains. This difference in data analysis may partly explain the qualitatively different trends of the two curves for smaller grain sizes and some of the shift of the two curves for larger grain sizes. In fact, on average one so-called packet (which contains the oscillations of a single particle impact) includes about 4.5 to 2 impulses for grain sizes varying from 14 mm to 85 mm [6]. In the AH analysis, the oscillation with the peak amplitude of a packet determines the grain size class, and further oscillations of the same packet (or particle) may be counted as impulses in lower classes. Thus the different assignment of smaller oscillations produced by a particle to the various grain size classes, as used for the derivation of the two curves in Fig. 5, may also well explain a part of the quantitative shift of the two curves.

## 5. Conclusion

The amplitude histogram method was developed for measurements with the Swiss plate geophone system using bedload samples at the Erlenbach stream. It is based on identifying grain-size classes as a function of the signal amplitude. In this study an earlier version of the AH method was refined by using a larger set of bedload samples from the Erlenbach. The new AH method also includes information on the impulse rates (as a proxy of bedload transport rates), and it resulted in a better agreement between the calculated and measured values of  $M$ ,  $D_{84}$ ,  $D_{75}$ , and  $D_{50}$ , as compared to the original AH method. A comparison with earlier flume experiments using bedload particles from the Erlenbach illustrated differences in the analyses of these two complementary data sets, which should be considered and discussed in more detail in a future study.

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