Calibration of Swiss Plate Geophone System for bedload monitoring in a sediment bypass tunnel

Ismail Albayrak, Michelle Mueller-Hagmann and Robert M. Boes

Abstract

Sediment bypass tunnels (SBTs) are one of the effective countermeasures against reservoir sedimentation for small to medium-sized mountainous reservoirs. They route sediment-laden flows around the dam, reduce sedimentation and improve morphology and ecology of downstream river reaches. However, high bedload transport rates in combination with high flow velocities cause severe hydroabrasion on the inverts of nearly all SBTs and hence considerable refurbishment costs. For optimized operation of SBTs with respect to sustainable sediment management and cost efficiency, continuous real-time monitoring of bedload transport is necessary. Bedload transport can be monitored indirectly by using passive sensors like geophones or hydrophones. However, these techniques require a site-specific calibration since they are affected by hydraulic conditions, particle size and shape. This study deals with the field calibration of the Swiss Plate Geophone System (SPGS) at the Solis SBT, Switzerland. The calibration procedure consisted of: (I) depositing 10 m^3 of bedload material for each particle-size class inside the tunnel, (II) running the SBT with surplus inflow after a flood event when discharge is high, thereby keeping a high reservoir level to avoid bedload transport from the reservoir entering the SBT, and (III) recording and analysing the raw geophone signals. Three particle-size classes were chosen: 16 – 32 mm, 32 – 63 mm and 0 – 400 mm. In this paper, the details of the SGPS at Solis SBT and the results of the field calibration are presented, compared and discussed with the results from two previous laboratory calibrations.

Keywords: bedload monitoring, high speed flow, Swiss Plate Geophone System, calibration, sediment bypass tunnel

1 Introduction

Sediment bypass tunnels (SBTs) are an effective and holistic countermeasure against reservoir sedimentation (Sumi *et al*. 2004, Boes *et al*. 2014) by routing sediments around a dam. A major problem affecting nearly all SBTs is severe hydro-abrasion on the tunnel invert due to high bedload transport rates and high flow velocities (Fig. 1). Invert abrasion can cause considerable refurbishment and maintenance costs. In the scope of a research project initiated by VAW of ETH Zurich, the hydroabrasion resistance of various invert materials was investigated at three case study SBTs in Switzerland (Hagmann *et al*. 2015, Mueller-Hagmann *et al*. 2017). The main goal of the project was to contribute to the sustainable use and design of SBTs suffering from severe hydroabrasion. To this end, abrasion depths and rates of the materials were quantified, hydraulic conditions were continuously monitored, and bedload transport rates were derived from the hydrographs at the case study SBTs. During operation of the Solis SBT located in Grisons, Eastern Swiss Alps, bedload transport was continuously monitored in real-time using the so-called Swiss Plate Geophone System (SPGS). The present study focusses on the calibration of the Solis SPGS.

The SPGS developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) is a robust device allowing for continuous bedload transport monitoring in a river (Rickenmann and McArdell 2007, Rickenmann and Fritschi 2010, Rickenmann *et al*. 2012, Rickenmann *et al*. 2013, Wyss *et al*. 2015, Koshiba *et al*. 2017). The plate is equipped with a geophone sensor which registers the vibrations of the plate, i.e. the vertical plate oscillations induced by impingement of passing particles. The number of impulses computed from the registered vibration signals correlates with the transported bedload mass. Using this correlation, i.e. calibration, bedload transport rates are estimated. However, calibration of a SPGS depends on flow velocity, particle size and shape, i.e. on site-specific conditions. Since prototype conditions cannot be reproduced in a laboratory, a field calibration is highly recommended.

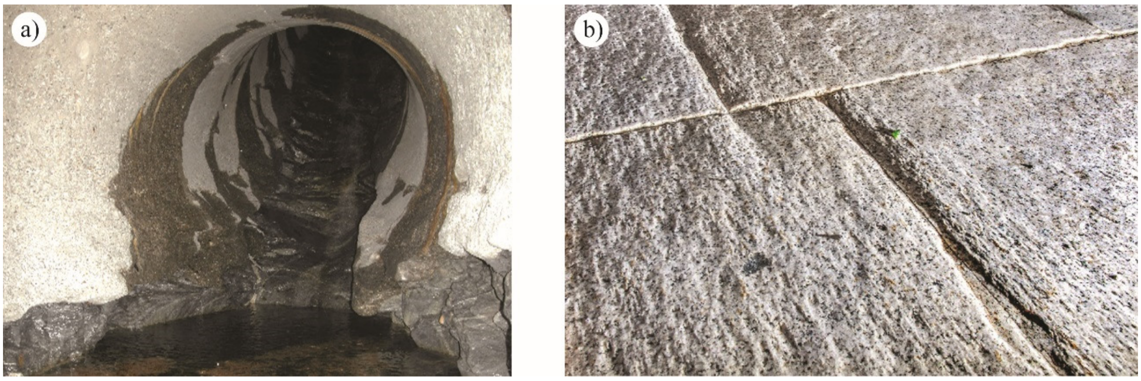

Figure 1: Hydroabrasion examples: a) deep abrasion into the concrete invert and rock underground at the Val d'Ambra SBT (photo: M. Müller-Hagmann), b) hydroabrasive damages at the granite lining of the Pfaffensprung SBT (photo: VAW) (adapted from Mueller-Hagmann 2017)

2 Test set-up and procedure

2.1 Solis SBT

The Solis reservoir was commissioned in 1986. Its initial storage volume amounted to approx. 4.07 10^6 m^3 of which 1.46 10^6 m^3 are used for power generation (active volume) by the electric power company of Zurich (ewz). The Albula River and the tailrace water of the ewz hydropower plant (HPP) Tiefencastel feed the reservoir.

On average, the estimated annual sediment volume transported to the Solis reservoir is 135'000 m^3 and the measured annual deposition volume is 110'000 m^3, of which 31'500 m^3 are excavated by a gravel plant (Mueller-Hagmann 2017). Until 2008, 25% of the reservoir storage capacity was lost due to sedimentation. To reduce the sedimentation and restore the interrupted sediment transport in the river reach, a 1 km long SBT with a slope of 1.9% was commissioned in 2012 (Fig. 2). Its intake structure is situated well below the reservoir drawdown level just downstream of the delta front location at the time of the SBT construction to stop the advancement of the latter towards the dam (Fig. 2). The inflows are therefore pressurized in normal SBT operation. The Solis SBT is planned to be put in operation at approach flow discharges of some 90 m^3/s (representing a one-year flood discharge) to bypass incoming sediments (Auel *et al*. 2011). However, a recent operation was also performed for a lower flood discharge of 80 m^3/s (Facchini *et al.* 2017). For an optimal bypass efficiency, the reservoir level has to be sufficiently lowered in advance of an incoming flood by turbining and/or releasing water through the bottom outlets. Only then the bed shear stresses are high enough to transport incoming bedload over the aggradation body of the delta to the SBT intake. The SBT operation needs to be carefully coordinated to avoid release surges in the tailwater of the dam.

Bedload particles entering the reservoir are diverted to the SBT intake by a guiding structure in the reservoir and then conveyed to the downstream river reach through the SBT (Fig. 2). With this design, the downstream part of the reservoir between the guiding structure and the dam is protected from sedimentation by both bedload and suspended load up to the SBT design discharge of 170 m^3/s, representing a five-year flood. For larger floods, quasi all bedload is still diverted by the guiding structure into the SBT, while the discharge exceeding the SBT design capacity and the corresponding suspended load will be conveyed towards the dam. The SBT efficiency in terms of bedload diversion is thus close to 1.0 (Facchini *et al.* 2017).

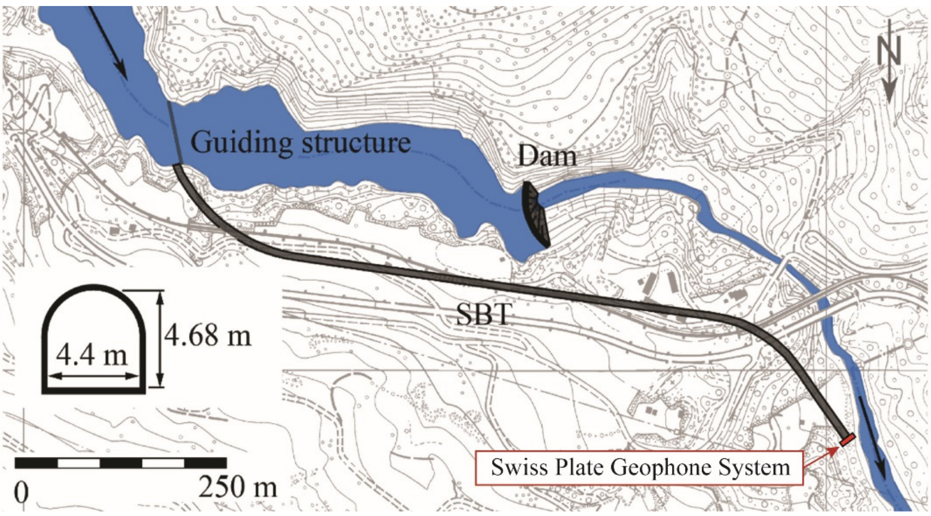

Figure 2: Overview of the Solis SBT with the dam (center), the guiding structure and intake (left) and the geophone system at the outlet (right) (adapted from Mueller-Hagmann 2017)

2.2 Swiss Plate Geophone System

The SPGS is a robust device allowing for continuous bedload transport monitoring (Rickenmann and Fritschi 2010, Koshiba *et al*. 2017) (Fig. 3a). It is typically used at a number of torrents and mountain streams with flow velocities up to 6.5 m/s and flow depth of a few decimeters, mainly in the Swiss and Austrian Alps. The device consists of an elastically bedded steel plate mounted flush to the channel bed. The plate is equipped with a geophone sensor (GS-20DX, manufactured by "Geospace Technologies", Houston, Texas), encased by a waterproof aluminum housing (Fig. 3a). The plate is 36 cm long in flow direction, 50 cm wide and 1.5 cm thick. The bearing between the plate and the mounting steel box is made of rubber, serving to isolate vibrational energy generated in the surroundings.

The geophone sensor registers the vibrations of the geophone plate induced by impingement of passing particles at 10 kHz (Fig. 3a and b). To filter out background noise and vibrations generated by flowing water, a threshold signal value of 0.1 V is defined in accordance with other applications (Rickenmann *et al*. 2013, Wyss 2016, Chiari *et al*. 2016). However, this threshold value may vary depending on background noise and other electronic interferences (Morach 2011).

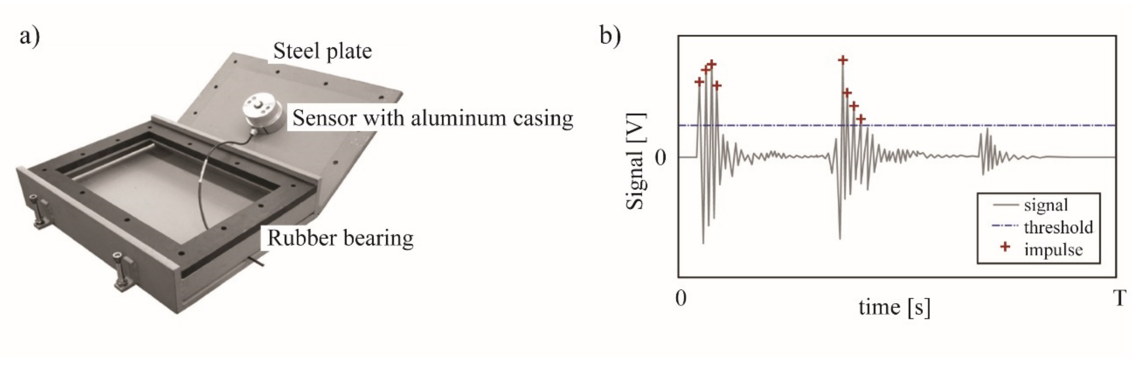

Figure 3: a) Swiss Plate Geophone System and b) schematic SPGS signal (adapted from Mueller-Hagmann *et al*. 2017)

An SPGS with eight units covering the entire tunnel width was implemented near the SBT outlet, 100 m downstream of a right hand bend (radius = 145 m, angle = 46.5°, Figs. 2 and 4a). A laboratory calibration was conducted before the implementation of the SPGS at the Solis SBT (Morach 2011). The results showed that particle detection rates increased with the inclination angle of the SPGS plate against the flow direction. Hence, the SPGS in Solis was accordingly implemented with an inclination angle of 10° (Fig. 4b). After the implementation, a further laboratory calibration similar to Morach's (2011) was conducted. The first and the second laboratory calibrations are called 'Morach' and 'Solis' hereafter, respectively, and their results are compared in section 3.

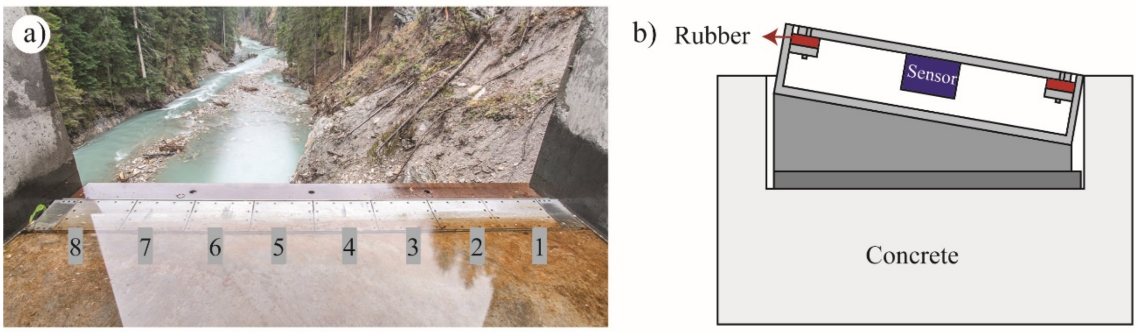

Figure 4: a) SPGS installed at the Solis SBT outlet consisting of eight geophones across the width, view in flow direction; b) Cross-section of a geophone, flow from right to left (adopted from Mueller-Hagmann *et al.* 2017)

2.3 Calibration coefficient K_b

The number of impulses Imp, above the threshold value (Fig. 3b) correlates linearly with bedload mass *m* (Rickenmann 1997, Rickenmann *et al.* 2012). The linear correlation coefficient is called 'calibration coefficient K_b' and defined as:

$$K_b = \mathrm{Imp}/m \text{ [1/kg]} \qquad [1]$$

As flow conditions, particle size and shape affect the calibration coefficient, an *in-situ* calibration of SPGS is necessary (Rickenmann and McArdell 2007, Rickenmann *et al.* 2012, 2013, Wyss *et al.* 2014, 2015, 2016a and 2016b). In general, the calibration is based on monitored sediment deposition volumes in retention basins or on basket sampling of transported sediment (Rickenmann and McArdell 2008, Rickenmann *et al.* 2012, 2014, Wyss 2016). As both methods are not feasible at Solis SBT, a controlled *in-situ* calibration was conducted instead as described below.

2.4 Calibration procedure and sediment characteristics

Three sediment size classes were used to calibrate the Solis SPGS (Fig. 5a). Three calibration runs, one for each sediment size class, were conducted. During the calibration, the steps described below were followed:

- Deposition of 10 m^3 of sediments downstream of the intake gate
- Operation of SBT at high reservoir level and signal recording
- Analysis of the raw SPGS signals

The SBT discharge was 50 m^3/s to limit water loss from the reservoir. The corresponding average flow velocity was 9.8 m/s. The reservoir water level was kept high at some 0.85 m below the full supply level, so that bed shear stresses were too low to entrain settled sediments at the upstream of the SBT intake.

The sediments used for the calibration were taken from a gravel plant, located on the Albula at the reservoir head. The grain size distributions (GSD) were provided by the supplier and checked by line-sampling. The GSDs are listed in Table 1 and shown in Fig. 5a.

For each calibration run, the sediments were weighed at the gravel plant and transported to the study site by truck. The sediments were deposited in the tunnel at a distance of 20 m from the intake gate and mechanically spread across the whole tunnel width with a layer thickness of 20 cm and a wedged forehead (Fig. 5b).

Table 1: Sediment properties of the calibration runs and the natural Solis sediment

	Name	D [mm]	d_m [mm]	Volume [m^3]	Mass [t = 10^3 kg]
Fine material	Calibration run 1	16-32 mm	25±2	10.01	15.3
Coarse material	Calibration run 2	32-63 mm	45±4	9.94	15.4
Mixture	Calibration run 3	0-400 mm	210±20	11.53	18.4
Solis natural	Solis GSD	0-300 mm	60	-	-

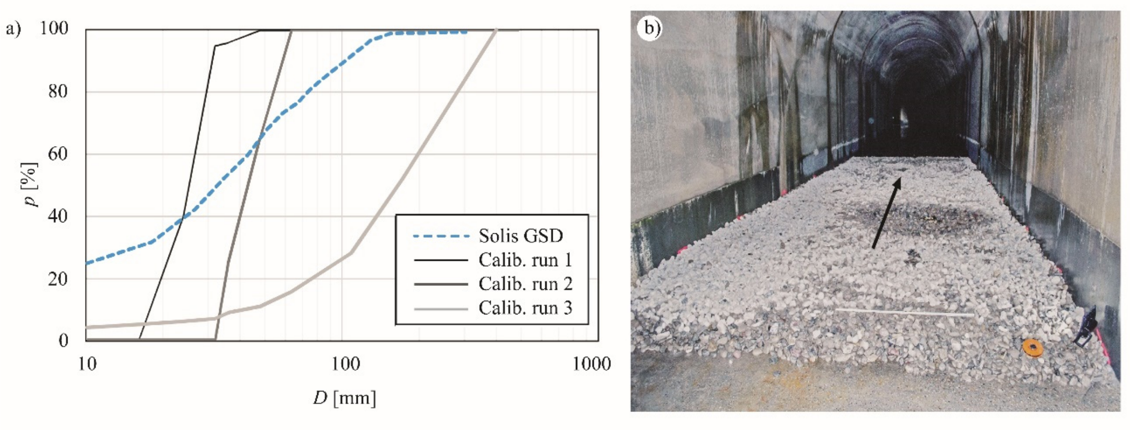

Figure 5: a) GSD of the calibration runs and the natural sediment at SBT Solis and b) photo of deposited sediments of size class 32 - 63 mm, view in flow direction (adapted from Mueller-Hagmann *et al.* 2017)

3 Results

An uneven bedload distribution across the tunnel width was observed during all three calibration runs. Figure 6a shows that sediment transport was concentrated at the right tunnel side (indicated by a darker flow area), and almost no particles were transported on the left side. The SPGS measurements confirm these observations (Figs. 6a and b) and indicate a strong effect of the upstream bend on the lateral sediment transport distribution. Figure 6b shows the relative number of registered impulses, i.e. the number of impulses per plate divided by the total number of impulses across the SBT width. The data collapse well irrespective of the calibration runs and thus GSDs. Similar lateral bedload transport distributions were measured with the SGPS during the previous SBT operations, confirming that the SGPS calibration runs reproduced the sediment transport under real Solis SBT operating conditions.

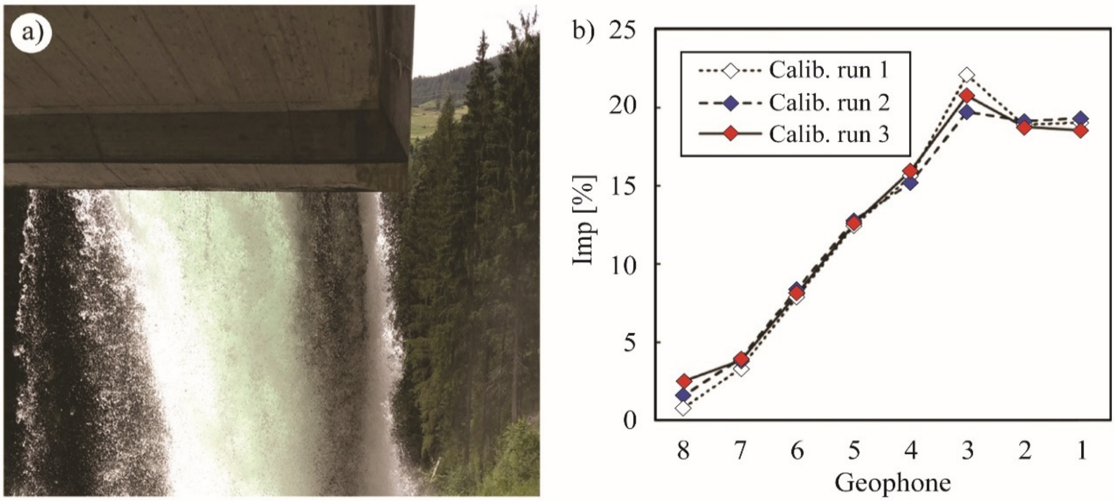

Figure 6: a) Photo from the outlet of Solis SBT during the calibration run 3 with *D*=0-400 mm and b) relative number of impulses registered by each geophone distributed across the tunnel width (adapted from Mueller-Hagmann *et al*. 2017)

The bedload calibration coefficient K_b determined for each calibration run is listed in Table 2. The present K_b values and the values obtained from Morach (2011) and the Solis laboratory calibrations are shown as a function of the corresponding grain size d_m in Figure 7. The mean flow velocity and specific gravimetric bedload transport rates of all three calibrations are listed in Table 3. The K_b values vary as a function of the grain size. Due to different hydraulic and bedload transport conditions of the calibrations, K_b values significantly scatter between the studies for the particles smaller than 50 mm. The difference between Morach's (2011) and the presented results may originate from the electric interferences causing a significantly higher background noise and amplified the signal, which bias the results, in particularly for small particles with low signal amplitudes in the range of the detection threshold. Regarding the particles larger than 50 mm, all K_b values are in a comparable range indicating that the effect of higher flow velocities on the K_b is reduced by higher bedload transport rates (Table 3). Note that increasing bedload transport rate causes overlapping of particle impacts on the plate, which results in signal damping and hence reduced number of impulses and K_b.

Table 2: Grain size and K_b based on the field calibration

	Calibration run 1	Calibration run 2	Calibration run 3
D (mm)	16 - 32	32 - 63	0 - 400
d_m (mm)	25 ± 2	45 ± 4	210 ± 20
K_b (1/kg)	6.80	13.6	5.05

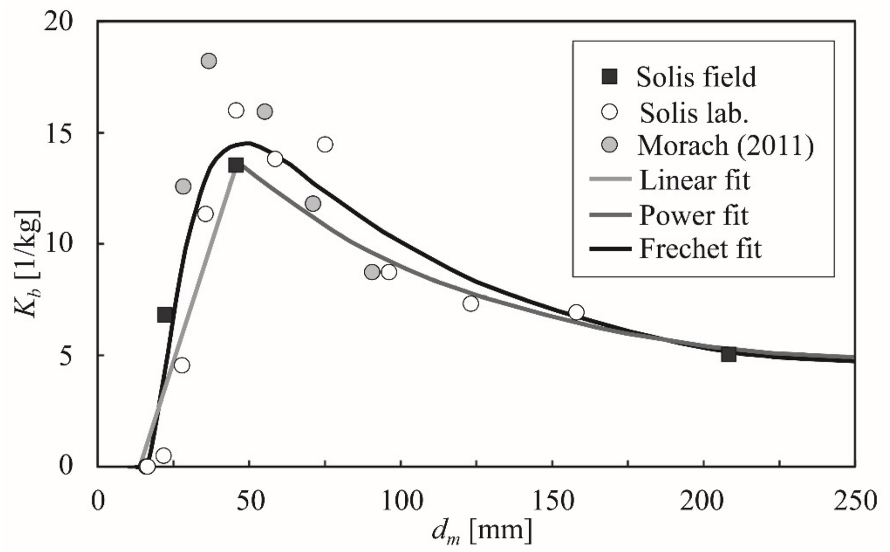

Figure 7: K_b values obtained from the Solis and Morach (2011) laboratory calibrations and the Solis field calibration as a function of d_m values with bimodal and Frechet fits of the field data (adapted from Mueller-Hagmann *et al.* 2017)

Table 3: Mean flow velocity U, and specific gravimetric bedload transport rates q_s of the Solis and Morach (2011) laboratory calibrations and the Solis field calibration

	Solis lab.	Morach (2011)	Solis field
U (m/s)	3	7.4	9.8
q_s (kg/s/m)	0.22 - 5.5 (mean 2.3)	6.7	68 - 83 (mean 74)

The data sets from the field and laboratory calibrations were fitted with (I) a bimodal function containing a linear (Eq. 2a) and a power fit (Eq. 2b) and (II) a Frechet distribution (Eq. 3) The values of the coefficients c_1 to c_8 were determined for each data set (Table 3).

$$K_b = c_1 \cdot D + c_2 \qquad [2a]$$

$$K_b = c_3 \cdot D^{c4} \qquad [2b]$$

$$K_b = c_5 \times c_6 \times c_7 \times c_8^{\,c_7} \times \left(1 - \mathrm{e}^{-\left(\frac{c_8}{D}\right)^{c_7}}\right)^{c_6 - 1} \times D^{(c_7+1)} \times \mathrm{e}^{-\left(\frac{c_8}{D}\right)^{c_7}} \qquad [3]$$

The K_b values to be used for the typical Solis SBT operating conditions were determined by applying a weighted averaging method based on the GSD of the Solis natural sediment (Table 1) using Eqs. (2a), (2b) and (3) with the corresponding coefficients c_1 to c_8. Considering the expected GSD at Solis SBT, the K_b values determined from the field calibration vary from 9.6 to 10.8 1/kg, which are comparable to those obtained from the Solis laboratory calibration (Table 4). The K_b values determined from Morach's data

(2011) are 10% to 20% higher than those from the other two calibrations. This deviation is due to electrical interferences that occurred during Morach's (2011) experiments, resulting in a threshold value of 0.2 V for Morach (2011) instead of 0.1 V. Therefore, Morach's data are only used for a plausibility check of the field results. Overall, K_b = (9.6+10.8)/2 = 10.2 1/kg, i.e. the averaged K_b value from the field calibration, is used to convert the recorded signals of the SPGS at Solis SBT to the bedload transport rates.

Table 4: Coefficients c_1 to c_8 obtained from the Bimodal and Frechet fits for the field and laboratory calibrations, coefficients of determination of the fits, and weighted averaged K_b for the expected GSD in Solis (Table 1)

	Bimodal fit						
	Linear fit			Power fit			
	c_1	c_2	R^2	c_3	c_4	R^2	K_b [1/kg]
Field Calib.	0.50	-6.7	0.92	175	-0.66	1.0	**9.6**
Solis Lab.	0.61	-11.4	0.98	344	-0.79	0.90	10.1
Morach	0.90	-13.8	0.99	367	-0.81	0.91	12.2

	Frechet fit						
	c_5	c_6	c_7	c_8	R^2		K_b [1/kg]
Field Calib.	15'000	0.044	1.85	48	0.93		**10.8**
Solis Lab.	7'800	0.054	2.77	43	0.98		10.7
Morach	2'200	0.279	2.4	40	0.99		11.6

4 Conclusions

A Swiss Plate Geophone System (SPGS) has been implemented at the Solis SBT for continuous and real time bedload transport monitoring. The system requires for a site-specific calibration. In this paper, the details of the SPGS at Solis SBT and the results of the field calibration are presented, compared and discussed with the results from two previous laboratory calibrations. Three calibration runs were conducted at Solis SBT, each having a different sediment size class. The present setup of the SPGS differs from the typical SPGS applications by an inclination of 10° against the bottom slope. The calibration coefficient K_b obtained from the field and laboratory calibrations did not show any dependency on the averaged flow velocity for the investigated range of velocities from 3 m/s to 10 m/s. A comparison between the field and laboratory calibrations reveals that K_b varies with particle size and hydraulic conditions. Therefore, a field calibration of the SPGS is recommended to limit the uncertainties in bedload transport prediction.

Furthermore, the weighted averaging method based on GSD is recommended to determine K_b.

The presented results are site-dependent and are only valid for the Solis SBT conditions and SPGS configuration. Based on the field calibration, the value of K_b = 10.2 1/kg is determined and used for the estimation of bedload transport rates at Solis SBT. To improve the accuracy of the calibration, further calibrations with more uniform and mixed sediment samples and a range of sediment transport rates similar to those during the typical SBT operations are needed.

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