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Author(s):

Müller-Hagmann, Michelle; [Albayrak, Ismail](#) ; [Boes, Robert](#)

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FIELD CALIBRATION OF BEDLOAD MONITORING SYSTEM IN A SEDIMENT BYPASS TUNNEL: SWISS PLATE GEOPHONE

MICHELLE MUELLER-HAGMANN⁽¹⁾, ISMAIL ALBAYRAK⁽²⁾ & ROBERT MICHAEL BOES⁽³⁾

^(1,2,3)Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Switzerland
mueller-hagmann@vaw.baug.ethz.ch; albayrak@vaw.baug.ethz.ch; boes@vaw.baug.ethz.ch

ABSTRACT

Under the impact of climate change, sediment transport in melting water draining from glacier basins and reservoir sedimentation tend to increase worldwide. As a consequence, three main problems arise: (1) the loss of reservoir storage volume for energy production, flood retention, water supply and irrigation; (2) increased hydro-abrasion at turbines and hydraulic structures; and (3) negative environmental impacts due to downstream sediment deficit. An effective countermeasure against reservoir sedimentation in small to medium-sized mountainous reservoirs is to route sediment around the dam by using a sediment bypass tunnel (SBT). A major problem affecting nearly all SBTs is severe hydro-abrasion on the tunnel invert due to high bed load transport rates in combination with high flow velocities. Depending on site-specific operating conditions and sediment properties, i.e. size, hardness and shape, invert abrasion can cause considerable refurbishment costs. For optimized operation of SBTs with respect to sustainable sediment management and cost efficiency, continuous real-time monitoring of bed load transport is necessary. Bed load transport can be monitored indirectly by using passive sensors like geophones or hydrophones. However, these techniques require a site-specific calibration depending on hydraulic conditions, particle-size and shape. This study deals with the field calibration of a so-called Swiss plate geophone system implemented at the outlet of Solis SBT located in Grisons in the Swiss Alps. The geophones with a sampling rate of 10 kHz are placed across the whole tunnel width and have an inclination of 10° against the invert slope. Three different particle size classes were tested 16-32 mm, 32-63 mm and 0-400 mm. The results indicate that calibration is independent from flow velocity due to the counter inclination of the geophones. However, a certain degree of signal saturation due to high bed load transport rate occurred and hence a further investigation is needed.

Keywords: Swiss plate geophone; bedload measurements; geophone calibration; sediment bypass tunnel; reservoir sedimentation.

1 INTRODUCTION

The role of sediment management considering sustainable and cost-effective operation and maintenance of hydraulic structures has been disregarded for a long time. However, sediment transport in watercourses increases due to the impact of climate change and promotes related problems such as a loss of storage volume for energy production, flood retention, water supply and irrigation, an increase of hydro-abrasive wear at turbines and hydraulic structures and negative environmental impact in the downstream due to the interrupted sediment transport by the dam (Sumi et al., 2004; Boes et al., 2014; Kondolf et al., 2014). Therefore, a holistic sediment management approach at hydraulic structures, in particular at reservoirs is globally required.

One of the effective and holistic countermeasures against reservoir sedimentation is to route sediment around a dam by using a sediment bypass tunnel (SBT). It restores the natural sediment transport and hence not only reduces reservoir sedimentation but also sediment deficit related problems in the downstream such as river bed incision, ground water lowering, degradation of eco-morphology, reduction of habitat quality and even nutrient and sediment deficit in coastal regions (Syvitski et al., 2005; Kantoush and Sumi, 2010; Fukuda et al., 2012; Fukuroi, 2012; Kondolf et al., 2014; Facchini et al., 2015; Martin et al., 2015). A major problem affecting nearly all SBTs is severe hydro-abrasion on the tunnel invert due to the high bed load transport rates in combination with high flow velocities (Figure 1). Depending on site-specific operating conditions and sediment properties, i.e. size, hardness and shape, invert abrasion can cause considerable refurbishment costs.

For optimized operation of SBTs with respect to sustainable sediment management and cost efficiency, continuous real-time monitoring of hydraulic operating conditions and sediment transport is required. The latter includes suspended sediment load and bed load and can be monitored by turbidity sensors and the Swiss Plate Geophone System (SPGS) described below, respectively. The number of impulses computed from the registered SPGS signals correlates with the transported bed load mass.

Using this relation, i.e. a calibration, bed load transport rates are estimated. Since flow velocity, particle-size and shape affect the calibration and because laboratory calibration cannot adequately reproduce prototype conditions, site-specific calibration in the field is highly recommended.

In the scope of a research project on the invert hydro-abrasion in SBTs, a field calibration of a SPGS was conducted. This system has been implemented at the outlet of Solis SBT located in Grisons in the Swiss Alps. The present study reports the results of the calibration and compares them with the results from two laboratory calibrations of the same system.

Figure 1. Hydroabrasion examples, a) abrasion at Val d'Ambra SBT (CH) into the concrete lining and rock underground (M. Müller-Hagmann), b) incision channels of the reinforced concrete lining of Asahi SBT (JP) (KEPCO, 2012), hydroabrasive damages at c) cast basalt tiles in Runchez SBT (CH) (M. Müller-Hagmann) and d) at the granite lining of Pfaffensprung SBT (CH) (VAW).

2 TEST SET-UP AND PROCEDURE

2.1 Solis SBT

The Solis reservoir located in the Swiss Alps was commissioned in 1986 and stores approximately $4.07 \cdot 10^6 \text{ m}^3$ of which $1.46 \cdot 10^6 \text{ m}^3$ are useful storage capacity for power generation by the electric power company of Zurich (ewz). Compared to the mean annual runoff of $853 \cdot 10^6 \text{ m}^3$, the reservoir volume and the capacity inflow ratio of 0.0048 are small. The reservoir is fed by the Albula River and the reservoir head is located one kilometer downstream of the confluence with the Julia River.

Estimated annual transported and deposited sediment volumes in the Solis reservoir are on average $103'000 \text{ m}^3$ and $80'000 \text{ m}^3$, respectively. After twelve years of operation, 20% of the reservoir storage capacity was lost due to sedimentation, which significantly affects hydropower operation. Assuming a constant aggradation rate, the aggradation body was expected to reach the dam by 2012 and would consequently have endangered the operation safety of the dam (Auel et al., 2011; Oertli & Auel, 2015). To reduce the sedimentation and restore the interrupted sediment transport in the river reach, a one-kilometer long SBT was constructed (Figure 2) and commissioned in 2012. The function of the SBT is to bypass incoming sediments during flood events. Bed load particles enter the reservoir and propagate towards a guiding structure in the reservoir, which diverts bed load to the SBT intake structure to be routed around the dam (Figure 2). With this design, the lower part of the reservoir between the guiding structure and the dam is protected from

sedimentation by both bed load and suspended load up to the SBT design discharge of $170 \text{ m}^3/\text{s}$, representing a five-year flood when the SBT is in operation. For reservoir inflows exceeding the design discharge, all the bed load is diverted to the SBT intake, whereas a part of the suspended load is conveyed towards the dam with the surplus flow passing the guiding structure. If not conveyed via the power waterway, the bottom outlet or the spillway to the tailwater, a considerable amount of fines may thus settle in the lower part of the reservoir, which is periodically flushed through the bottom outlet.

Since the SBT intake is located below the drawdown level, the inflow is pressurized and no acceleration section is required. After the intake, the SBT flow is decelerated but remains supercritical with Froude number $F \approx 1.7$ and an average flow velocity of $U \approx 11 \text{ m/s}$. Hence, a sufficient sediment transport capacity is ensured along the whole tunnel. The bottom slope of the SBT is 1.9%, and the arched cross sectional area amounts to 18.5 m^2 .

Figure 2. Overview of the Solis SBT with the dam (center), the guiding structure and intake (right) and the geophone system at the outlet (left).

2.2 Swiss plate geophone system

The SPGS developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) is a robust device allowing for continuous bed load transport monitoring (Rickenmann & Fritschi, 2010; Koshiba et al., 2017). There is a long-time experience with SPGS at a number of torrents and mountain streams with flow velocities up to 5 m/s and flow depth of a few decimeters, mainly in the Swiss and Austrian Alps. The submersible device consists of an elastically bedded steel plate mounted flush to the channel bed. The plate is equipped with a geophone sensor (shown in Figure 3a: GS-20DX, manufactured by “Geospace Technologies”, Houston, Texas), encased by a waterproof aluminum housing (Figure 3b). The length of the plate in flow direction is 36 cm , the width is 50 cm and the thickness is 1.5 cm . The bearing between the steel plate and the mounting steel box is made of rubber (elastomer type CR/SRB-standard 65 ± 5 , manufactured by “Angst + Pfister”, Zurich, Switzerland). Besides signal damping issues, this bearing serves for isolation of vibrational energy generated in the surroundings.

The sensor does not directly measure bed load transport, but registers the vibration signals of the geophone plate, i.e. the vertical plate oscillations induced by impingement of passing particles. The signal output is a voltage with a sampling frequency of 10 kHz (Figure 4). To filter out background noise and vibrations generated by clear water discharge, 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 can be changed depending on background noise and other electronic interferences (Morach, 2011).

Figure 3. SPGS: a) geophone sensor (courtesy of Geospace Technologies) and b) open measuring unit showing steel plate and waterproof aluminum housing of the sensor.

Figure 4. Schematic geophone signal.

2.3 Calibration coefficient K_b

The number of impulses Imp above the threshold value (Figure 4) correlates linearly with bed load mass m (Rickenmann 1997, Rickenmann et al. 2012). The linear correlation coefficient between impulses and bedload mass K_b is used to estimate sediment transport rate. It constitutes a calibration coefficient and is defined as:

$$K_b = \frac{Imp}{m} \quad (1/kg) \quad [1]$$

Recent investigations reveal that not only sediment transport rate but also grain size information can be extracted from the amplitude of the geophone signals (Wyss et al., 2014; Wyss, 2016; Wyss et al., 2016a). Since the calibration coefficient is affected by flow conditions, grain size and shape, a site-specific calibration is required (Rickenmann and McArdell, 2007; Rickenmann et al., 2012; Rickenmann et al., 2013; Wyss et al., 2014; Wyss et al., 2015; Wyss et al., 2016a and 2016b). The calibration is generally based on monitored sediment deposition volumes in retention basins or on basket sampling of transported sediment (Rickenmann and McArdell, 2008; Rickenmann et al., 2012; Rickenmann et al., 2014; Wyss, 2016). However, as none of these methods is possible at Solis SBT, a field test described in Section 2.2. was performed to calibrate the geophone system at the Solis SBT.

The SPGS was implemented near the SBT outlet, 100 m downstream of a right hand bend (radius = 145 m, angle = 46.5°, Figure 2). In order to capture not only temporal but also spatial variations of bed load transport, the SPGS at Solis SBT consists of 8 units covering the entire tunnel width (Figure 5a). In contrast to the general geophone applications, the flow regime in the Solis SBT is supercritical. To address this issues, a laboratory investigation was conducted before the implementation of the SPGS in the Solis SBT (Morach, 2011). The tests revealed that particle detection rates increased when inclining the geophone plate against the flow direction compared to the horizontal mounting. Thus, the geophone system in Solis was accordingly implemented with an inclination angle of 10° (Figure 5b). After the implementation, further laboratory tests

similar to Morach (2011) were conducted, the results of which are compared with the present results in Section 3.

Figure 5. a) Counter-inclined SPGS installed at the Solis SBT outlet; view in flow direction; b) Cross section of the geophone construction (flow from right to left).

2.4 Procedure and characteristics of sediments used

The Solis SPGS (Figure 5a) was calibrated using three sediment grain size classes. Three test runs, one for each sediment size class, were conducted. The calibration procedure consisted of: (I) placing of a 10 m³ sediment deposit volume downstream of the intake gate, (II) SBT operation and signal recording, and (III) analysis of the raw geophone signals. The sediment deposit was located at the inlet in order to achieve characteristic bedload transport of typical SBT operation. To limit water loss from the reservoir, a discharge of 50 m³/s was selected. To avoid additional sediment transport from the reservoir, the reservoir level was kept high (i.e. 0.83-0.85 m below the full supply level), so that bed shear stresses were too low to entrain settled sediments. The sediments used for the geophone calibration were taken from a gravel plant, located on the Albula at the reservoir head so that the sediment properties were identical to the sediment transported through the SBT in typical operations. The grain size distributions (GSD) were provided by the supplier and checked by line-sampling (Table 1 and Figure 6a). Based on the latter, the corresponding gravimetric GSD was calculated according to Fehr (1987). Therefore, the fraction of the particles smaller than 16 mm was assumed to 15%. For each test run, the sediments were weighed at the gravel plant and transported to the test site by truck. Due to limited space, a side- and back-dumper was used. At a distance of 20 m from the intake, the sediments were damped and distributed by a small excavator. The sediment deposition covered the whole tunnel width with a layer thickness of 20 cm and a wedged forehead (Figure 6b).

Table 1. Sediment of the calibration test runs and the natural Solis sediment.

	Name	D (mm)	d_m (mm)	Volume (m ³)	Mass (to)
Fine material	Test 1	16-32 mm	25±2	10.01	15.3
Coarse material	Test 2	32-63 mm	45±4	9.94	15.4
Mixture	Test 3	0-400 mm	210±20	11.53	18.4
Solis natural (assumed)	Solis GSD	0-300 mm	60	-	-

Figure 6. a) GSD of the natural sediments flushed through the SBT and of the sediments used for geophone field calibration; b) photo of damped sediments of size class 32-63 mm, view in flow direction.

3 RESULTS ON THE CALIBRATION COEFFICIENT K_b

Figure 7a shows the sediment-laden flow at the SBT outlet structure, depicting that: (1) bed load distribution across the tunnel width was uneven during all three test runs, (2) sediment transport was concentrated at the right tunnel side, see darker flow area, and (3) almost no particles were transported on the left side. These qualitative observations were confirmed by the quantitative geophone measurements indicating a strong effect of the upstream bend on the lateral sediment transport distribution (Figure 7b). 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, collapses well independent from test run and thus GSD (Figure 7b). During normal SBT operation, similar lateral bed load transport distributions were measured, which confirms that the geophone calibration tests reproduced the real sediment transport conditions in the Solis SBT.

The bedload calibration coefficient K_b was determined for each test run (Table 2). Figure 8 shows K_b versus grain size D for the Solis field and laboratory calibration tests as well as Morach's (2011) tests. The geophone can detect the particles with a size above $D = 16$ mm and thus around this threshold particle size, K_b is approx. zero (Figure 8). As expected, K_b varies with particle size (Morach, 2011; Wyss, 2016). Despite different hydraulic and bed load transport conditions, all K_b values are in a comparable range, in particular for particles larger than 50 mm. For $D \approx 25$ mm the K_b value of the field calibration is higher than for the laboratory calibration, while it is the contrary for $D \approx 45$ mm. This is attributed to the higher flow velocity prevailing in the Solis SBT. The difference between Morach's (2011) and the presented results may originate from electric interferences affecting Morach's experiments. Her measurements exhibit a significantly higher background noise, which can amplify the signal and hence bias the results, in particularly for small sediment with low amplitudes in the range of the detection threshold.

Figure 7. a) SBT outlet with clear water and black sediment jet on the right side during the test run 3 with $D=0-400$ mm, view in flow direction from underneath the SBT outlet; b) relative number of impulses registered by each geophone plate.

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

	Test 1	Test 2	Test 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 8. K_b versus D for the laboratory and field calibration as well as Morach's (2011) results with a bimodal correlation as well as a Frechet fit for the field data.

The data sets from the field and laboratory calibrations were fitted with (I) a bimodal function containing a linear raising (Equation [2a]) and a power law falling limb (Equation [2b]) and (II) a Frechet distribution (Equation [3]), which was already successfully applied by Wyss (Wyss, 2016; Wyss et al., 2016a, b), where c_1 to c_8 are the coefficients determined for each data set (Table 3).

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

$$K_b = c_3 \cdot D^{c_4} \quad [2b]$$

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

The K_b values to be used for the typical Solis SBT operating conditions, i.e. outside the calibration tests presented herein, 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 only the expected GSD at Solis, 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 laboratory calibration tests (Table 3). The K_b values determined from Morach's (2011) test data are 10 to 20% higher than those from the other two calibrations (Table 3). This difference is attributed to different impulse threshold values among the calibration tests, i.e. 0.2 V for Morach (2011) and 0.1 V for the other two calibrations. Therefore, these results are only used for a plausibility check confirming the field results. Finally, $K_b = (9.6+10.8)/2 = 10.2$ 1/kg, i.e. the averaged K_b from the field calibration, is used for the Solis SBT SPGS.

The bimodal (Eqs. [2a] and [2b]) and the Frechet fits (Eq. [3]) were also applied to the GSD of Test 3 (Figure 6a) to verify the applicability of the weighted averaging method. The calculated K_b values for Test 3 are 5.1 1/kg and 5.8 1/kg and deviate by only 1 and 15%, respectively, from $K_b = 5.05$ 1/kg directly obtained from the field calibration (Table 2). This result confirms that for a given GSD the method using either bimodal or Frechet fits results in a good prediction of K_b .

Table 3. Bimodal and Frechet fits for the field and laboratory calibration as well as for Morach's (2011) data describing the correlation between K_b and D with the corresponding coefficients of determination and resulting weighted averaged K_b for the expected GSD in Solis (Table 1)

	Bimodal fit						Frechet fit						
	Linear fit			Power fit			K_b	c_5	c_6	c_7	c_8	R^2	K_b
	c_1	c_2	R^2	c_3	c_4	R^2	(1/kg)						(1/kg)
Field	0.5	-6.7	0.92	175	-0.66	1.0	9.6	15'000	0.044	1.85	48	0.93	10.8
Lab	0.6	-11.4	0.98	344	-0.79	0.90	10.1	7'800	0.054	2.77	43	0.98	10.7
Morach	0.9	-13.8	0.99	367	-0.81	0.91	12.2	2'200	0.279	2.4	40	0.99	11.6

The effect of geophone inclination on the calibration coefficient K_b is analyzed by comparing the present laboratory and field data as well as Morach's (2011) data (10° inclination) with the data from Rickenmann et al. (2013) (approximately 0° inclination). In Figure 9 the K_b values of the particles with $D > 16$ mm are plotted as a function of average flow velocities. Rickenmann et al. (2013) data feature a decreasing trend with increasing flow velocity, whereas the rest of the data does not show a velocity dependency. This difference can be attributed to the geophone inclination. However, to support this hypothesis, further tests with different relative grain submergence, grain size, sediment transport rates and impulse counting thresholds values are required.

Figure 9. K_b as a function of mean flow velocity and geophone inclination; data from Rickenmann et al. (2013), Morach (2011) and from laboratory as well as field calibration experiments for the Solis SBT

4 CONCLUSIONS

A Swiss plate geophone system (SPGS) at Solis SBT was calibrated with three sediment size classes under field conditions. This system differs from the typical SPGS applications by an inclination of 10° against the bottom slope. The results are compared with those from two laboratory calibration tests with the same inclination and literature data for approximately 0° inclination slightly varying depending on the river bed slope. The calibration coefficient K_b obtained from the laboratory and field tests did not show any dependency on averaged flow velocity, while the literature values indicate a decreasing trend with increasing flow velocity. This leads to a general conclusion that the geophone inclination affects K_b . A comparison between the laboratory and field tests reveals that K_b varies with particle size, relative particle submergence and hydraulic conditions. Therefore, a field calibration of the SPGS is recommended to limit the uncertainties in bed load 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 results of the laboratory and field calibrations, $K_b = 10.2$ 1/kg was found for the geophone system at the Solis SBT. To improve the accuracy of the calibration, further tests with more uniform and mixed sediment samples and a range of sediment transport rates similar to typical SBT operation are needed.

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