Laboratory Research and Development of Bedload Impact-Plate Sensors

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ABSTRACT

Quantification of sediment transport in rivers is critically important to many areas of river engineering and restoration. Here we report on an effort to develop a technology for continuous monitoring of bedload transport in rivers that utilizes advanced technologies for measuring sound and vibrations generated by impacts of moving gravel on a steel plate mounted in the bed of a river. The premise of the technology assumes that the frequency of vibration or sound is correlated with the mean size of particles in transport and the intensity of the sound (volume) is correlated with flux rate. The study involves exploration of field-deployable sensor technologies and data acquisition hardware, development of advanced, real-time, time series analysis techniques, and full-scale laboratory testing and calibration of the system in a large gravel-recirculation channel. The sensors tested in the study include a hydrophone, accelerometer, and geophone. Data acquisition techniques were developed for high frequency sampling of gravel impacts, and through the research we developed time-series analysis techniques that allow real-time estimates of bedload.

INTRODUCTION

The research reported here focuses on an effort to develop an impact-plate sensor and data acquisition system that can be used in the field at the newly developed bedload monitoring site on the Elwha River in Washington, USA. The development is part of the Elwha River Restoration Project near Port Angeles, Washington. The planned removal of the Elwha Dam and Glines Canyon Dam is expected to release large volumes of clay, silt, sand, gravel, and cobbles to the Elwha River. Construction of a new surface water diversion facility downstream from the two large dams provided an ideal opportunity to install bedload impact sensors across the bed of the Elwha River channel to continuously monitor bedload that passes through the section. More

information on the Elwha River Restoration project can be found in a companion paper by Hilldale et al.

In this paper we present research on an emerging bedload surrogate technology – the bedload impact-plate sensor. The operational concept for this technology is based on recording the local vibrations and sounds produced as moving bed material strikes a steel plate. These recordings are translated, through calibration, into estimates of bedload flux and potentially grain size. Figure 1 shows a schematic of the impact-plate sensor system. A sensor is mounted on the underside of a steel plate. The plate rests on a steel frame that is securely fixed into the streambed. Wires from the sensor pass through the steel box to the side of the channel and a data acquisition system.

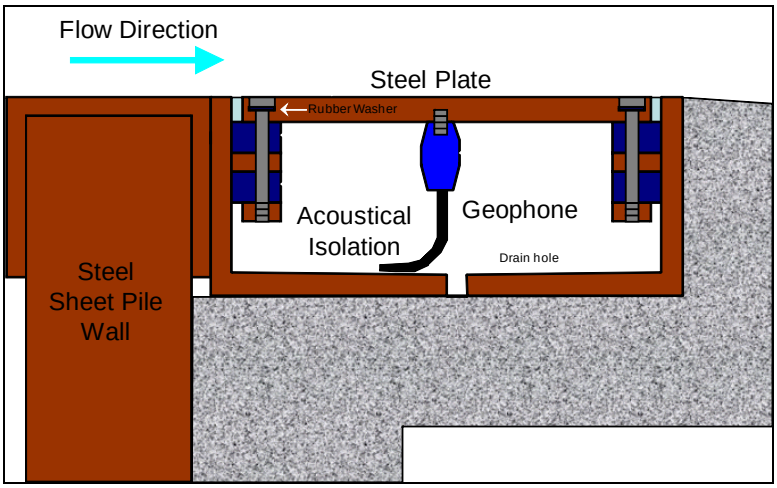

Figure 1. Schematic of impact-plate sensor system shown with a geophone.

Impact-plates have seen limited use over the last decade. The Swiss Federal Research Institute has tested these devices using geophone and piezoelectric sensors and reports positive results (Rickenmann and McArdell, 2007). Norwegian researchers have also performed laboratory and field studies on bedload impact-plates (Bogen and Møen, 2003) including exploration of the use of a spectral analyzer that outputs the spectral density of frequency resulting from particle impacts. The results of this work indicate that the frequency distribution and intensity of the signal are linked to the grainsize and flux of material striking the plate.

The goal of this research was to develop a prototype system of bedload impact sensors and data acquisition software that can be used in gravel bed rivers including the Elwha system. The research took place at the St. Anthony Falls Laboratory (SAFL), University of Minnesota. Two test facilities were used in the research in which full-scale sediment transport and data acquisition of impacts were recorded. Substantial effort was placed on developing techniques to provide real-time analysis of the data. The goal for the analysis tool was to develop a computationally efficient means of translating the time-series signal generated by the sensor into an estimate of flux rate and grain size of the transported bed material. Analysis techniques include 1) methods of counting rock strikes by signal thresholding, and 2) advanced analytical techniques including analysis of the power spectral density of the time-series and dominant frequencies. Both of these analytical techniques can be used real-time and

serve to translate the data into estimates of bedload flux. We focus on the advanced techniques in this paper.

SENSOR RESEARCH AND SELECTION

A first task in this project was an investigation into the various sensor technologies available while evaluating cost, robustness, performance in water, and frequency ranges. Three technologies were chosen for the experimental investigations: geophones, hydrophones, and high-frequency accelerometers. Table 1 gives pertinent information on the selected sensors.

Table 1. Sensors Selected for use in the Bedload Impact-plates.

	Dynamic Range	Manufacturer	Model
Geophone	20-200 Hz	Geospace, LP	GS-20DM
Hydrophone	0.1 Hz to 180 kHz	Bruel & Kjaer	8103
Accelerometer	0.32 Hz to 10 kHz	STI	CMCP-1100

SENSOR MOUNTING

All sensors were flush mounted to the underside of a rectangular sheet of steel and this steel-sensor assembly was set into a frame, resting on rubber gasket material. The gasket material served to dynamically isolate the plate so that cross-talk between neighboring plates was minimized. The accelerometer and geophone were mounted with a small stud attachment to the underside of the plate. The hydrophone was attached to the underside of the plate using a steel block with a rabbit groove machined in the center. Each plate was then attached to the frame.

DATA ACQUISITION SYSTEM DESIGN

The hardware and software for collecting information from the installed impact-plates and sensors were selected as part of this project. The research team determined that it was important for the data acquisition system to have the capability of sampling frequency as high as 50,000 Hz. Standard data logger systems do not have the sampling speed to achieve this. The research team decided on a PC-based data acquisition system that included a programmable computer and monitor, analog/ digital data acquisition card and data acquisition software. National Instruments LabVIEW software was chosen for application development. A high-speed data acquisition card was chosen for the A/D conversion and sampling.

LABORATORY STUDIES

A series of laboratory tests were conducted at the SAFL to prototype the impact-plate technologies and develop a robust data acquisition system.

In the first phase of testing a flume was designed to accommodate a prototype impact-plate enclosure with two, side by side plates. This research and development phase was motivated by very fundamental questions about the physical operation of the impact-plates and the limitations of the acoustic and vibration properties one can measure from a submerged rock impact. Rocks of four sizes (100mm, 50mm, 22mm and 8mm in diameter) were dropped at various locations on the plates to map the variation in response based on size and distance from the mounted sensor. Data

acquisition software was developed and used during these preliminary tests. Figure 2 shows results from the hydrophone for 100mm and 50mm particles. For strikes at the same location, smaller particles generate smaller signals than larger particles.

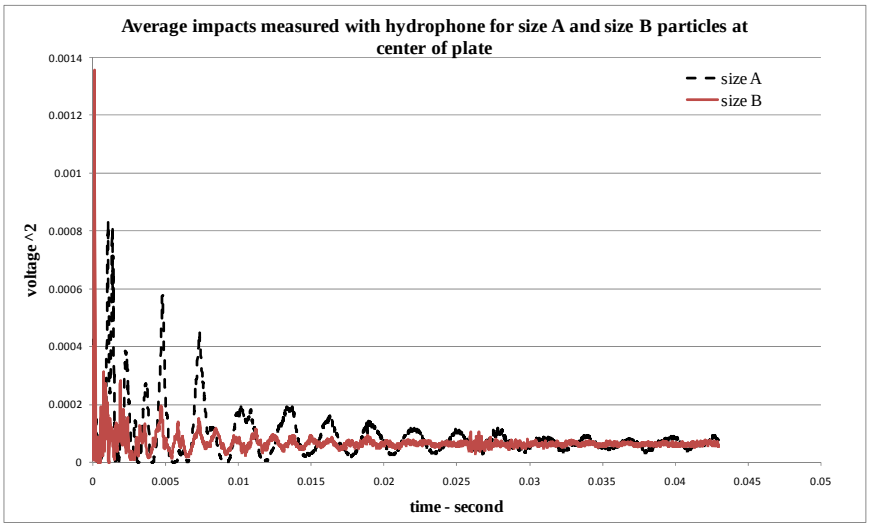

Figure 2. Plot of average voltage response from single particle impacts at the plate center of 100mm and 50mm particles measured by a hydrophone.

Figure 3 shows data collected from the submerged geophone. A 100mm rock was dropped from a height of 5cm at three locations: 0, 5, and 20cm from the center of the plate (the sensor is mounted in the center). The data show that the amplitude of the voltage response diminished with distance from the sensor. These results are quite important since they indicate that the amplitude of the measured voltage response to a single strike is a function of both particle size and location of the strike. The same observation was made for the hydrophone sensor and for different sizes particles.

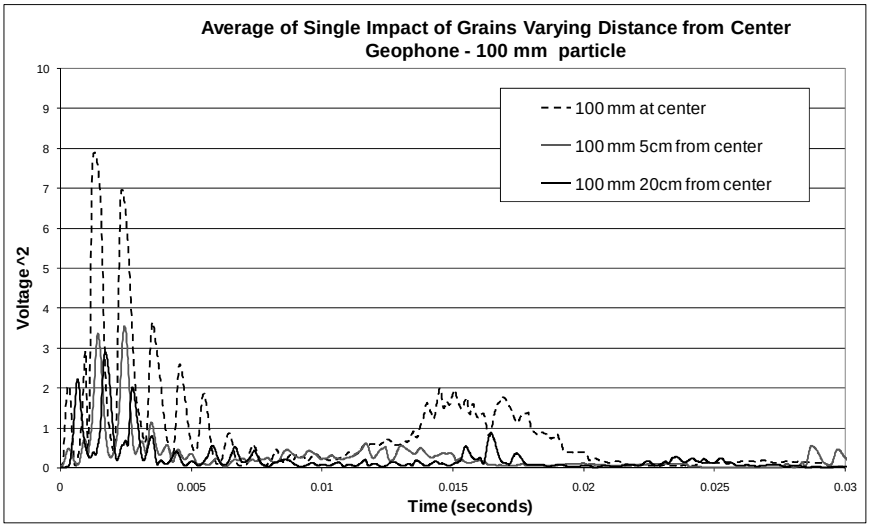

Figure 3. Voltage data recorded from the geophone with impacts from a 100mm particle on the plate surface. The particle was dropped vertically onto the plate at various distances from center: 0, 5 and 20 cm for the geophone.

From these results we can conclude that the measured voltage response from a strike is not unique to rock size; a rock of a single size can have a range of voltage responses depending on how it strikes the plate. This observation may limit the ability of the impact-plate sensor to discern grain size.

Main Channel Testing

A second phase of testing took place in the Main Channel Facility of SAFL and involved a full-scale performance evaluation of a three-plate enclosure. The plates were subjected to mixed-size bedload transport (up to 32mm gravel) at a range of rates. Response data recorded from the sensors was used to develop and refine data acquisition systems and real-time data processing capabilities that provide estimates of bed-material flux.

The Main Channel is an indoor research channel with a rectangular cross-section that measures 2.8 meters in width and 1.8 meters in depth. Water for the channel is sourced from the Mississippi River by controlled diversion of water through an intake structure. The maximum discharge through the channel is 8.5 m^3/s.

Approximately 55 meters from the upstream end of the flume is the Sediment Monitoring and Recirculation System (SRMS) which has the ability to capture, weigh, and recirculate gravel-sized bed material. Fifteen meters downstream of the SMRS is a sharp crested weir with the dual purpose of controlling tail water elevation and instrumented monitoring of water discharge. Full details of the Main Channel system can be found in Singh et. al. (2009).

The gravel used in the study was a custom mix of three readily available local aggregates that were mixed at a ready-mix facility in a known ratio. This final distribution was a unimodal lognormal distribution with a D_{16}, D_{50}, and D_{84} of 4.3mm, 11mm, and 23mm, respectively.

A three panel impact-plate assembly was constructed and installed in the channel (Figure 5). This assembly houses a hydrophone, accelerometer, and geophone on three adjacent plates.

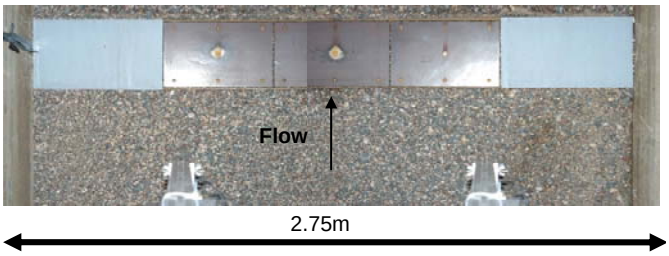

Figure 5. Plan-view image of impact-plate assembly installed in the SAFL Main Channel. Blank plates are located at the edges.

Data were collected over five water discharges from 1500 to 2800 L/s resulting in five separate flux conditions. Impact-plate data for each of the three sensors were collected in 15 minute intervals over a one hour period. The following accompanying datasets were recorded along with the impact-plate sensors:

Total bed-material flux: The Main Channel's SMRS recorded continuous total sediment flux out of the test section ~15m downstream of the plates. This system is

calibrated to provide an accurate record of bed-material flux in the flume and was used to ground-truth various other sediment monitoring technologies.

Local bed elevation: A bed-tracking sonar transducer was positioned 1m upstream of the center impact-plate and recorded bed elevation changes at 1 second intervals.

Local Bedload flux: An Elwha handheld bedload sampler was used to measure local bedload flux rates during data collection. Ten samples were taken over a one-hour period and these data were time-stamped such that they could be compared with the local bed elevation data. Samples were processed streamside for flux and grain size.

The plates were installed into a streambed that had been equilibrated to the design discharge for over 30 hrs of runtime. The assembly was installed high so that flow accelerated over the top of the structure and prevented deposition on the plates - a required criteria for the plates as deposition on top of the plates makes them useless.

Main Channel Results

The goal of the main channel work was to collect data that will be used to develop calibration methods for linking voltage response of the sensors to bed material flux in gravel-bed rivers. Data acquisition software was used to develop real-time acquisition and processing capabilities that can be used in the field. The data processing of these signals involved 1) measuring a time-series of voltage response, 2) processing the mean power spectral density (PSD) for a set duration of recorded signals, 3) computing the total power contained under the mean PSD, and 4) outputting this information to the user.

Time series and power spectral density

The time-domain data collected in the flume can be transformed into the frequency domain using Fast Fourier Transforms or other similar techniques. These methods allow us to view the impacts as distribution of power over a range of frequencies. The monitoring system developed is based in the frequency-domain information. Figure 6 shows an example of raw data collected with the accelerometer over 5 seconds and the same data converted into the frequency domain. In this plot, we see that the dominant frequencies are in the 1,000-10,000 Hz range.

To quantify the information contaminated in the frequency data, we compute total power by summing the area under the curve over a range of frequencies. For the results presented here, we sum the returns from 1000-10,000 Hz. Total power allows us to represent a single time-series of data as a single data point of total power.

Figure 7 shows a summary of performance of the impact-plates sensors developed in this testing. The plot shows a comparison between impact-plate response (total power) and bed elevation over time. Through the local bedload flux measurements made with the handheld sampler, we can show that local bedload flux is correlated with bed elevation of the bedforms; the highest transport rates are observed at the bedform crests. In the plot below, we show that total power from the impact-plates sensors also follows bed elevation. The (+) symbols are the bed elevation measured 1 meter upstream of the center impact-plate. Each symbol in the colored lines represents average total power over a 60 second period.

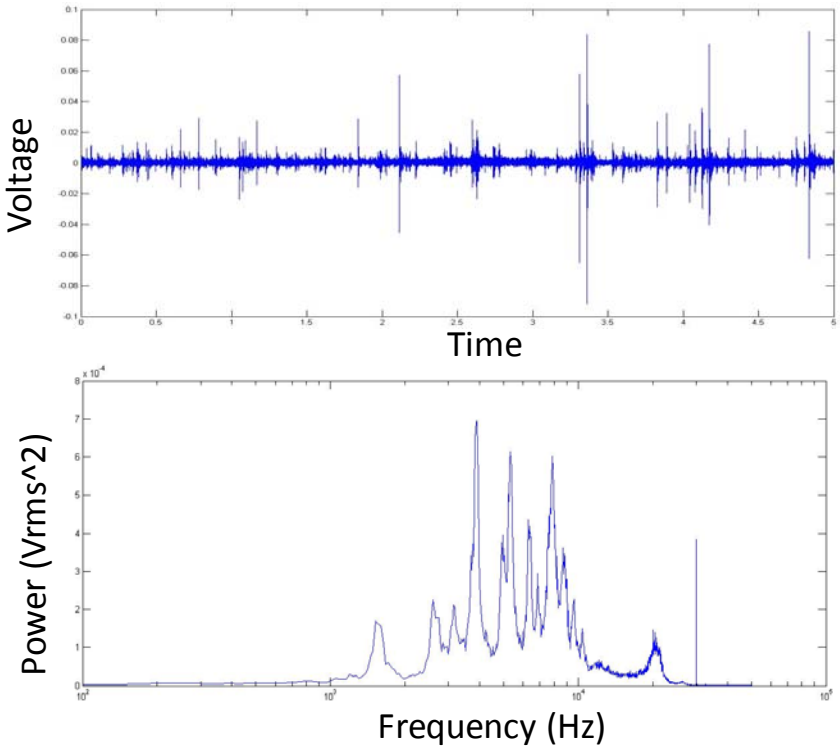

Figure 6. Example of time-domain information converted into frequency-domain.

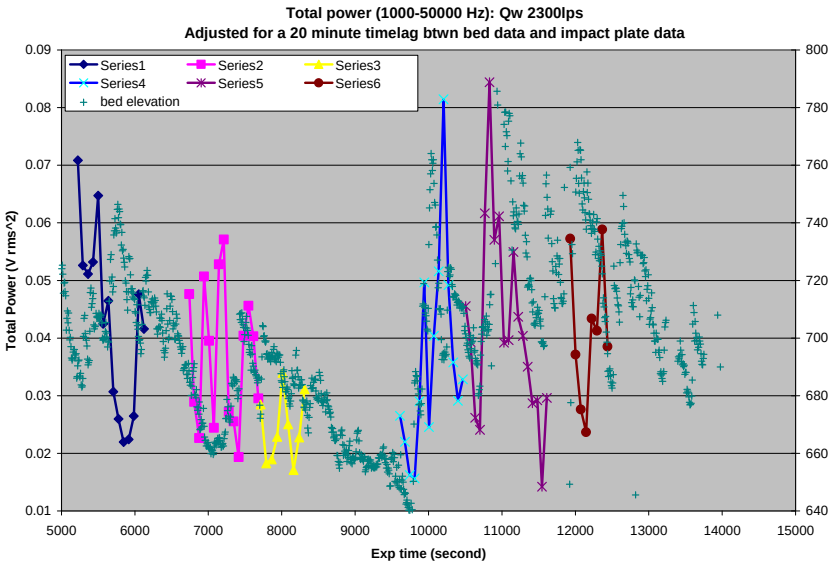

Figure 7. Correlation between bed elevation as measured by the upstream sonar and the total power recorded by the accelerometer. The two data sets are lagged 20 minutes to account for the 1 meter distance between the bed sensor and the impact-plates.

CONCLUSIONS

The research results from the laboratory testing show that it is possible to continuously monitor the bedload flux of gravel in a laboratory setting using the impact-plate bedload sensor. Only a quick overview of the essential finding is presented in this paper. The research into the fundamental physical of the impact-plate showed that a single impact of a particle could result in a range of responses from the sensor depending on impact location. Other causes of variability found were angle of impact and multiple impacts. All these factors lead to the conclusion that it is not possible to identify individual particle size with this system. The approach presented here is therefore based on a broader view of all the sounds/vibrations occurring over a longer duration of time, e.g. approximately one minute. Time-series voltage data recorded from the sensors are converted into the frequency-domain using Fast Fourier Transforms and, from this data, total power is computed. A data acquisition application was created as part of this project and will be applied to a bedload monitoring site on the Elwha River in Washington, USA.

The Main Channel Experiments show good correlation between total power and local sediment flux, which was measured indirectly by bed elevation (position on the bedform) and directly with handheld bedload samplers. By performing site-specific field calibrations with conventional samplers, it will be possible to correlate the output of the impact-plate sensors (total power and power distribution) to a bedload sediment flux. Future research will focused on further developing the approaches outlined here and extending this to a field-deployable system.

ACKNOWLEDGEMENTS

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