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Acoustic gravel-transport sensor: description and field tests in Little Granite Creek, Wyoming, USA

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Abstract Acoustic systems have been developed for the measurement of bed load momentum in gravel bed streams. The transducers are placed in the bed load either by a wading operator (GTS-I) or in a fixed installation embedded in the stream (GTS-II). The signals produced when particles impact the transducer are processed by an electronics unit to provide a continuous record of bed load momentum. A recent comparison of a GTS-II system with bed load traps in a small, mountain stream yielded promising results. Although the data are limited, they show that when the size of the bed load is known, corrections for grain velocity are made, and time-space averaging is sufficient, GTS measurements are roughly comparable to those made with bed load traps.

Key words bed load; bed load transport; gravel bed streams; gravel-transport sensor

INTRODUCTION

An understanding of bed load transport in gravel bed streams is needed for the assessment of the ecological and physical consequences of land-use changes in and around these systems. D & A Instrument Company is developing acoustic systems for measuring bed load in streams and on beaches to meet this need. The idea of using acoustic signals generated when entrained sediment particles strike a rigid object is not new. Sharp & O'Neill (1968) used a wire to detect sediment flowing in pipes and Downing (1981) used a similar technique to measure sand bed load in streams. In the early 1990s, this approach was extended to measure gravel bed load with a pipe containing an acoustic detector and recording electronics (Downing, 1993). In this paper, we describe further developments of acoustic devices for measuring gravel momentum and present the results of our tests in a small, mountain stream in Wyoming, USA.

SENSOR DESCRIPTIONS

The gravel-transport sensor (GTS) consists of a 1.6-mm, 17-PH4, stainless steel pressure plate covering a sheet of 0.5-mm PVDF film (PiezoFlex™, AIRMAR Technology Corp.), the acoustic detector, backed by a mass of aluminium; see Figs 1 and 2. When gravel collides with the plate, it compresses the detector until its forward

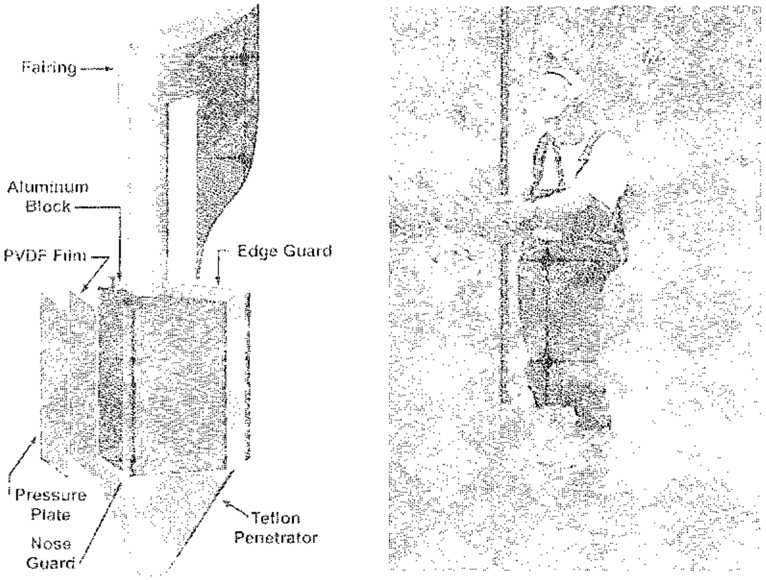

Fig. 1 Exploded view of GTS-I transducer and photograph of GTS system during a stream survey.

Fig. 2 Photographs of GTS-II transducer, anchor assembly (insert) and sensors deployed with bed load traps in Little Granite Creek.

momentum is expended then it bounces back into the flow. Nearly all of the strain produced by an impact occurs in the PVDF film because of its low elastic modulus (1%) relative to the adjacent elements. Electric charge is generated by the PVDF film in proportion to the force exerted on the pressure plate and the time integral of force, the impulse, is proportional to the momentum of the impacting particles. The integral of electrical charge is therefore a direct measure of particle momentum. PVDF film was selected from several candidate piezoelectric elements because of its high sensitivity, excellent formability, and low mechanical quality (a bell has high mechanical quality), elastic modulus, and cost. Laboratory calibrations have demonstrated that transducers constructed in this way are sensitive to particle momentum in the range 0.00002–0.08 kg m s^{-1}. The lower end of this range is equivalent to a 5-mm stone moving at 0.12 m s^{-1} and the upper end represents a 100-mm stone moving at 0.06 m s^{-1}. The calibrations also show that sensitivity is very uniform over the transducer area because the pressure plate is very stiff. Tests with steel balls dropped onto a grid of 18 evenly spaced points on a GTS transducer showed that the coefficient of variation of the output was only 2.3%.

The GTS transducer has been configured for two applications (Downing, 2003). The first one, called GTS-I, is for a handheld unit deployed by a wading operator in much the same way as a Helley-Smith bed load sampler is used. Figure 1 shows an exploded view of the GTS-I transducer design. Two 54 × 105-mm PVDF elements are bonded to a block of anodized, 7075-T6 aluminium with high-strength epoxy in a 90°, open-book configuration. The leading edge of the assembly is protected from impact damage with a steel bull nose bonded into the front of the mounting block and the trailing edges are protected with an edge guard bolted to the back of the transducer. The open-book geometry was chosen so that impact angles are nearly constant. This is the angle between a particle trajectory prior to impact and the pressure plate. It is important because the correlation between particle momentum and impulse (the charge integral) depends on the impact angle. When pointed upstream, the impact angle is 45° and the cross-flow active area of the GTS-I transducer is 76 mm wide. Figure 1 also shows a GTS-I deployed in a stream. Electrical connections to the PVDF film are made through holes in the film and the leads are routed to the electronics through passages in the mounting structure.

During sampling, the operator positions the GTS-I at a point on a sample transect and steps on it to force the Teflon® penetrator into the streambed. Once in position, a switch is depressed to initiate a sample record. At the end of a sample, the switch is depressed again to stop recording. This process is repeated at several positions to complete a transect. To reduce operator fatigue, a plastic fairing (CWA Products, Ltd) is fixed to the submerged part of the device (Fig. 1) to reduce drag by about 85% relative to a cylindrical shape with the same cross section. The pole is made of carbon-fibre composite for stiffness, low weight, and low heat loss and the device can be broken down into 1.5-m lengths for shipment. The GTS-I assembly weighs 4.6 kg.

The second application is an embedded sensor mounted on an anchor assembly containing batteries, electronics, and a data logger that can record bed load transport for periods from a few weeks to several months (GTS-II). Figure 2 shows two GTS-II transducers, an anchor assembly (inset), and a stream installation beside bed load traps developed by Bunte *et al.* (2001). The construction of the sensor is similar to that described above, except that only one PDVF element is used and the active cross-section is 95 × 200 mm. The GTS-II system also has a pressure transducer for measuring depth along with momentum data.

The electronics consist of an analog signal processor, a low-power microcontroller, and a FLASH data-storage circuit. Signals from the acoustic detector are input to a charge amplifier, the output of which is fed to a fourth-order, 500-Hz, high-pass filter that removes 60-Hz and other low-frequency noise. The filter output is routed to a comparator through a variable-gain amplifier that provides electronic compensation

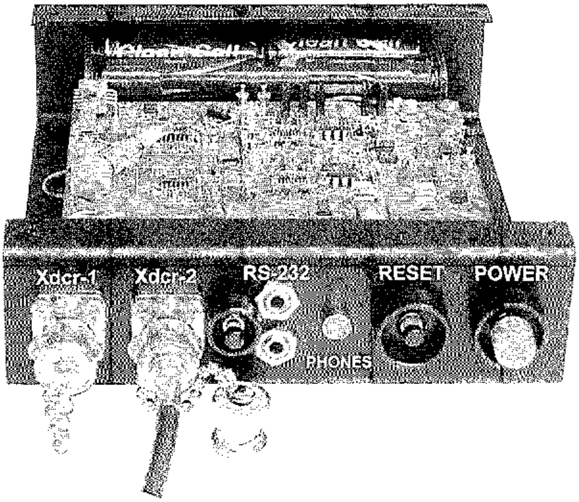

Fig. 3 GTS electronics and operator controls.

for differences in transducer sensitivity. When a signal produced by an impact rises above the comparator threshold, the comparator switches to a logic-high state until the signal returns to ground. The resulting square wave connects the signal to an integrator and triggers a pulse timer and a one shot to signal the microcontroller to digitize and record the integrator output and pulse duration. Once peak acquisition is complete, the controller resets the logic and integrator to set them up for the next pulse. The pulse acquisition time of the microcontroller is 7 ms, resulting in a maximum pulse-acquisition rate of 143 Hz. Because of FLASH memory limitations, the controller computes the average peak area and peak duration over an operator-selectable period from 1 to 60 s and stores the average values along with the number of impacts and time and date. The data FLASH can record 18 400 samples, which corresponds to a 306-h record for a sample period of 60 s. From laboratory tests with granitic and sedimentary stones, pulse durations range from 10 to 200 μs. Pulse duration is a data-quality-assurance parameter that indicates if the data are noisy and of dubious quality. The electronics and operator interface are shown in Fig. 3. The GTS-I transducers were calibrated by dropping steel balls and stones, falling at terminal velocity, on to the submerged transducers and recording the integrator counts. Integrator counts are an exact, digital measure of peak area. The calibration data for the transducers used in Little Granite Creek are shown on Fig. 4.

FIELD TESTS

The field tests were conducted in Little Granite Creek, which is an upland contributor to the Snake River system situated in the Gros Ventre range near Jackson, Wyoming, USA. Little Granite Creek is described by Ryan & Emmett (2002). Upstream of the GTS installation, the creek drains 19.7 km^2 of sandstone and interbedded sandstone and claystone. In the upper reaches, above the test site, several active landslides feed

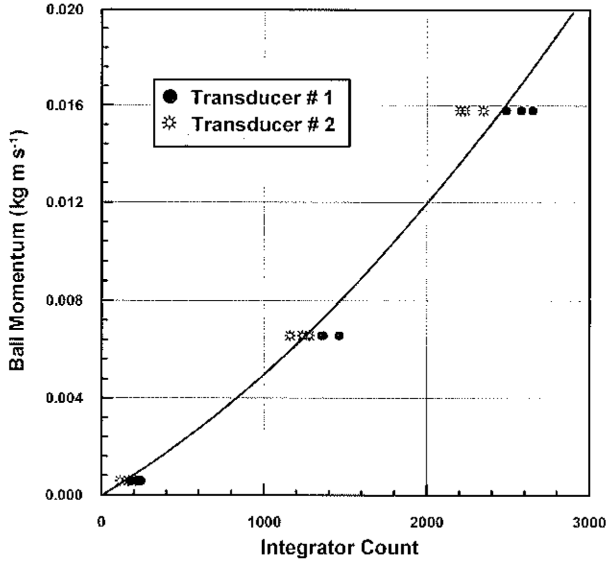

Fig. 4 Steel-ball calibrations of transducers used in Little Granite Creek (integrator counts are equivalent to peak areas).

glacial outwash and till to the creek where the channel has step-pool and plane-bed sections. The mean channel slope in the study reach is 0.021 and the local slope on the bar where samplers were deployed is 0.0115. Channel width and mean depth are 6.5 m and 0.34 m, respectively. At bankfull flow (3.4 m^3 s^{-1}), the mean velocity is 1.5 m s^{-1}. The streambed surface at the test location is composed of sand, gravel, and boulders and has a median grain size (d_{50}) of 49 mm determined by a pebble count.

The bed load sampler is 0.3 m wide, 0.2 high, and has a 0.9-m long trailing net with a 3.9-mm mesh. For sampling, the trap is temporarily fastened to a ground plate anchored in the stream bottom with steel rods. Sampling times are usually 1 h facilitating representative samples of a wide range of transport rates (up to seven orders of magnitude) and bed load particle sizes (4–90 mm). Two GTS-II sensors and two portable traps were installed on a submerged bar of the channel (Fig. 3) from 26 May until 9 June 2002 during snowmelt runoff. The prototype GTS-electronics box was placed on the stream bank and connected to the transducers with cables.

In order to compare the GTS record with trap samples, the data were binned each hour and the average depth, total impact counts, and the average peak areas in integrator counts were computed. Counts were then converted to average momentum using the calibration results shown in Fig. 4 and the total momentum in a 1-h bin is the product of the average momentum and the impact count. The values were divided by the cross-stream width of the transducers in metres to get bed load momentum in kg m s^{-1} per metre of bed per hour.

The GTS measures bed load momentum whereas direct samplers capture a mass of it. In order to compare GTS and bed load-sampler observations, it is necessary to factor bed load velocity into one set of the numbers. We elected to factor it into the bed load samples by using particle velocities computed from stream hydraulics and trap samples sieved in 0.5-phi size classes. Using the method described below, the velocity of each size fraction in a sample was computed and multiplied by the fraction weight to get fractional momentum. The total momentum of all fractions was then calculated. These results were divided by the trap width in metres and sampling time to get the bed load momentum per metre of bed per hour.

Equation 1, originally developed by Sekine & Kikkawa (1992) and later modified by Papanicolaou *et al.* (2002), provides a way to compute average particle velocities during saltation events from particle size, friction, critical-friction, and fall velocities. The equation was calibrated in a flume with fixed-bed roughness of uniform size, which yielded standard errors of about 14% of the mean velocity. It has not been verified in a natural stream. Critical-friction velocities were estimated using an equation given by Wilcock & Crowe (2003). Friction velocities were estimated using $U_* = (gSh)^{1/2}$ and a record of local water depth and bed slope, where: g = gravitational acceleration; S = energy gradient, nearly equal to the local bed slope; and h = local depth (Engelund & Fredsoe, 1976). Particle velocity is:

$$U_p = \sqrt{Rgd}\left[1.7\frac{U^*}{\omega}\sqrt{1-\frac{U^*c}{U^*}}+0.10\right] \qquad (1)$$

Where: R = relative submerged density $(\rho_s - \rho)/\rho$; ρ = water density (kg m^{-3}), ρ_s = sediment density (2650 kg m^{-3}); d = particle diameter (m); ω = fall velocity (m s^{-1}); and U_{*c} = critical-friction velocity (m s^{-1}).

The results of the comparison for 28 May until 3 June are shown in Fig. 5. The bold trace shows the bed load momentum computed from the GTS record and the fine trace shows the water discharge measured at a gauging station 50 m upstream. Gravel began to move around noon on 28 May and continued to move intermittently until noon on 2 June. Prominent transport events occurred at 92, 113, and 128 h, the last of which was the largest one recorded. Momentum computed for the trap samples is shown by the open symbols.

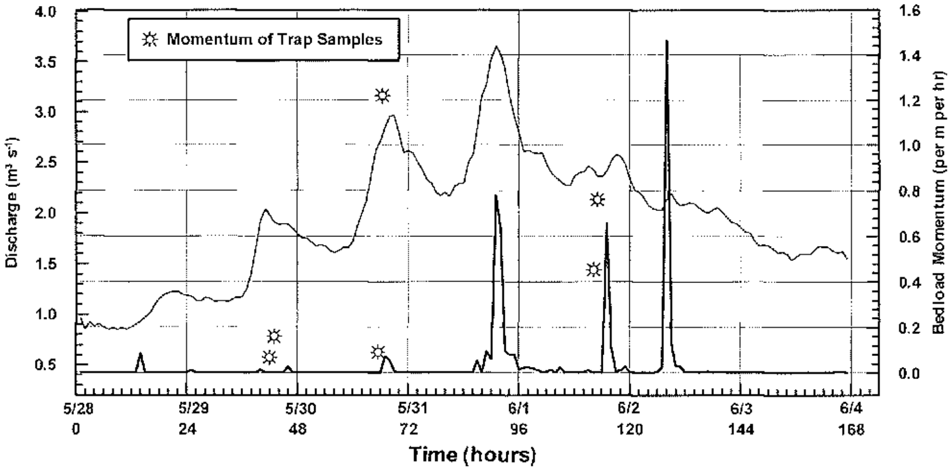

Fig. 5 Time series of discharge (fine trace), bed load momentum (bold trace), and computed momentum for trap samples (open symbols).

DISCUSSION

As the field tests have demonstrated, some bed load events occur when trap operators are not on the scene. The main advantage of the GTS-II system is that it provides a continuous record of the onset, relative magnitude, and cessation of transport events. The GTS-II is installed vertically with the bed surface located at the middle of the active transducer area, unlike some other sensors that are placed across a stream, flush with the bed. With this orientation, the bed can move up and down with accretion and erosion one half the transducer length, and moving grains will still impact the sensor. The disadvantage of the installation is that the sampling intensity is less than flush-mounted sensors. Sampling intensity is the percentage of the total bed load that is sampled. For example, a bed load sensor that spans an entire channel and monitors continuously would have a sampling intensity of 100%. Sampling intensities for the devices used at Little Granite Creek are much lower, ranging from 0.5, 2.4, to 7.5% for the Helley-Smith samplers, GTS-II sensors, and bed load traps, respectively. In many situations, continuous records from low-intensity sensors are worth more than records from high-intensity sensors with data gaps. The choice of one over the other will depend on the study objectives.

The data show general agreement with respect to magnitude most of the time. However, there is a poor correlation between the trap samples and the timing of peaks in the continuous GTS record. Sometimes the results from the two techniques agree quite well, such as for one of the samples around hour 68 and the one at hour 113, but at other times computed values differ by a factor of 14 and greater. Part of the difference is explained by the uncertainty of the particle velocities. Observations by Lee *et al.* (2000), indicate that the average velocities of saltating particles are normally distributed with a standard deviation of about 15% of the mean velocity. Time averaging should therefore remove the effects of these random velocity fluctuations. A more likely explanation for the time correlation is that transport rates vary greatly in time over the width of the channel during transport events. For example, the ratio of gravel masses trapped simultaneously about one metre apart were: 0.9, 10.9, 16.7, 30.4, 8.7, and 5.2, indicating that large differences are possible between closely spaced devices. This order of variability has been observed in transects made with Helley-Smith samplers at nearby sites and in other streams (Ryan & Porth, 1999). Although limited in scope, the test showed that GTS measurements are roughly comparable to those made with bed load traps when the size of the bed load is known, corrections for grain velocity are made, and time-space averaging is sufficient. It is clear, however, that longer sampling times extending over a wider range of transport conditions will be required to produce statistically significant calibrations.

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