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Laboratory Calibration of a Magnetic Bed Load Movement Detector

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Abstract

A series of laboratory experiments was conducted to test and calibrate the Bedload Movement Detector (BMD), a magnetic system for measuring coarse bedload movement in gravel bed rivers. Empirical relations were derived between the amplitude, width and integral of the sensor response, and particle size, magnetic content and velocity. Because of high variability in magnetic field strength across the sensor face, the system is highly sensitive to particle trajectory; therefore the present design of the BMD system cannot be used to reliably predict the particle size from an individual signal.

Introduction

Magnetic detection systems are designed to track the movement of either artificially tagged, or naturally magnetic coarse particles (for review see Bunte and Ergenzinger, 1989; Hassan and Ergenzinger, 2003). The underlying principle is that when a magnet passes over an iron-cored coil of wire (an inductor), a measurable electronic pulse is generated.

The first known system of this kind was built by Ergenzinger and Conrady (1982). They inserted magnets into pebbles, and a magnetic detector was used to monitor their passage. The second, a similar but more advanced system developed by Ergenzinger and Conrady, was used to detect the passage of naturally magnetic cobbles and pebbles past a fixed point during flow events in Squaw Creek, Montana (Ergenzinger and Custer 1983; Custer et al., 1987, Bunte, 1996). It was estimated that the system was sensitive enough to detect 40% of the coarse material (>32 mm) in Squaw Creek. The passage of particles was recorded on a strip chart recorder. This made data analysis time consuming, and limited the resolution of the system to approximately 200 particles per hour (Spieker and Ergenzinger, 1990; Bunte, 1996).

The third magnetic system was developed by Reid et al. (1984). Their system consisted of two elongated unscreened coils; the sensors were fully balanced over the entire width of the channel. The passage of the particles over the sensor distorted the magnetic field and produced a change in the inductance of the coils. To avoid double registration of tracers and the influence of particles settling on or very close to the system, a self balancing system was built into the circuit that tuned out the influence of such particles after a predetermined time interval. The system operated automatically and was activated by circuit closure in a mercury tilt-switch that was attached to the water level recorder. The main advantage of these systems is automatic operation and the tracking of individual particles during mobilizing flow events. However, the systems are fixed in one position.

The most recent magnetic system was developed by Tunnicliffe et al (2000), and is referred to as the BMD (Bedload Magnetic Detector) system. Figure 1 shows a schematic diagram of this system. The sensor is made with a copper coil set inside a strong, vertically magnetized doughnut-shaped magnet. As a stone moves into the magnetic field of the sensor, the magnetic minerals in the stone align with the field, and produce an induced magnetization (M). As the stone passes over the coil, the changing magnetic field (dM/dt) produces a voltage response in the coil. The sensor is connected to an analog-digital recorder, and voltage is regularly sampled.

In this paper we present an attempt to calibrate the BMD system, the most recent and advanced system of this kind.

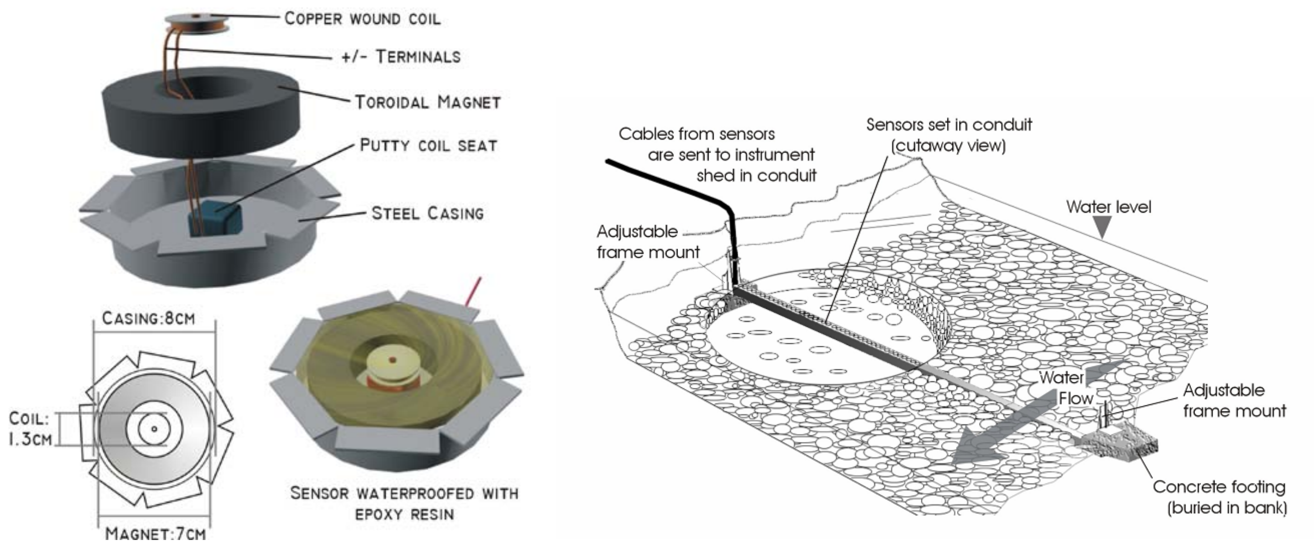

Figure 1: Schematic diagram of the BMD (Bedload Movement Detector) magnetic system (after Tunnicliffe et al., 2000). (a) A schematic view of an individual sensor, showing the three components: the coil, the magnet, and the steel casing. (b) A schematic view of the BMD system installation in the field.

Calibration

Rotating platter experiments (Figure 2) were designed to isolate variables and build models relating the sensor's voltage response and particle size. The experiments assessed 5 variables associated with the particle: particle volume, magnetic susceptibility, velocity, and vertical and horizontal trajectory. Magnetic susceptibility is a unitless quantity that describes how strongly an object is magnetized in an external magnetic field. The magnitude of susceptibility is dominated by the amount of magnetite and to lesser extent other ferromagnetic minerals in the rock. Particles with higher susceptibility produce stronger responses when they pass over the sensor.

To control particle size (volume) and susceptibility, artificial stones (spheroids) were created using different mixtures of cement, sand and iron filing for 8 size classes ranging from 8-90 mm diameter. To control particle velocity and trajectory (vertical and horizontal) as they passed the sensors, particles were placed on a Styrofoam platter which rotated beneath two BMD sensors. Because the BMD sensors are placed in an array across the channel, two sensors were used in the experiments to test if/when the same particle would produced a signal in both sensors. The vertical and horizontal distance could be altered by changing the platter height or the sensor position, but the stones' radii from the centre of rotation remained constant. Particle speeds were varied from 0.6 to 2.4 m/s to reflect a range of velocities likely to be found in the field.

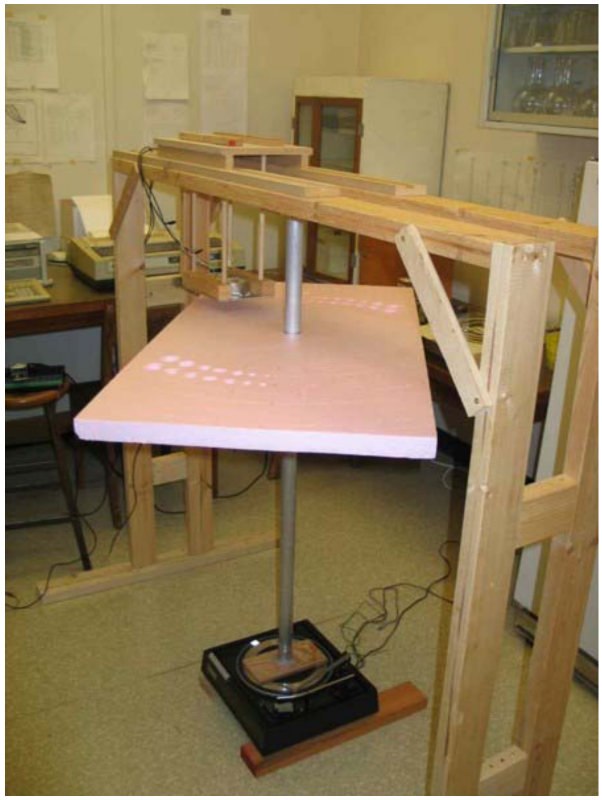

Figure 2: Rotating platter apparatus, designed to control particle trajectory and velocity.

Analysis

Signal Processing

Figure 3 shows a typical voltage response from a passing particle. The response has the shape of a gaussian derivative. For all of the calibration experiments, the data acquisition system sampled at a frequency of 501.19Hz. Before analysis, the data were filtered with a low pass butterworth filter at 45Hz to block out excess high frequency noise. The data were then run through a peak/valley detection sequence to identify the individual responses. For each individual response, the amplitude, width, and integral of the response were calculated. Signal width was calculated as the time difference between the peak and the valley. The integration of the curve was calculated as the average of the area under the peak and the area under the valley from zero crossing to zero crossing, using the trapezoidal rule.

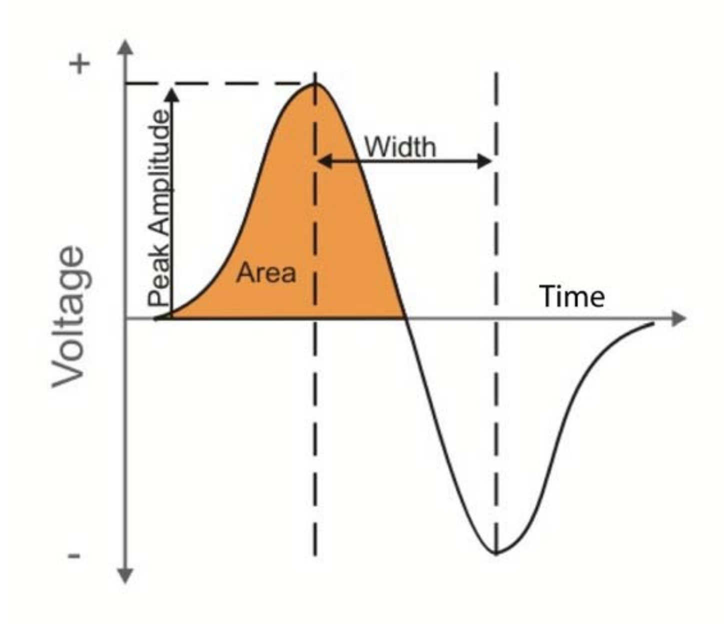

Figure 3: Typical voltage response to a particle passing over the BMD, and associated signal parameters used for analysis.

Empirical Models

Based on a theoretical understanding of the sensor physics, signal amplitude is a function of particle size, susceptibility and velocity; increasing any of the parameters will increase signal amplitude. Signal width is a measure of the length of time it takes the particle to pass over the sensor, which is a function of velocity and diameter of the passing stone. Since it is only a function of position and time, it is independent of the particle susceptibility, eliminating one unknown. The signal integral is a function of the particle size and susceptibility, but is independent of velocity. If the same stone were to pass by at two different velocities, the signal produced by the faster particle would have larger peak/valley amplitudes, but also a narrower width; the area under the curve, however, is conserved.

Using results from the rotating platter experiments, data were examined by multiple regression to develop empirical models relating the signal parameters (amplitude, width and integral) to particle size, susceptibility and velocity. The empirical models were then inverted to solve for particle size.

Of the three signal parameters, the empirical model for signal width produced the poorest results; it was not possible to differentiate particle size based on signal width. The signal amplitude and signal integral models were similar; however, the signal integral model is simpler to compute since the integral is independent of particle velocity, and in field applications, it is likely that the velocity will not be known.

Figure 4 shows the relation between signal integral and particle size. The plot includes data from a range of particle velocities, and is sorted by particle susceptibility. The trend in the log-log plot indicates a power relation. The slopes of the relationships are consistent between the different particle susceptibilities, but the y-intercepts increase with susceptibility. The slopes appear to flatten for volumes above 12 cm^3, suggesting that, for larger particles, the top portion of the particle does not contribute as strongly to the signal response due to its distance from the sensor. Due to this break in slope, separate models were developed for particles above and below 12 cm^3.

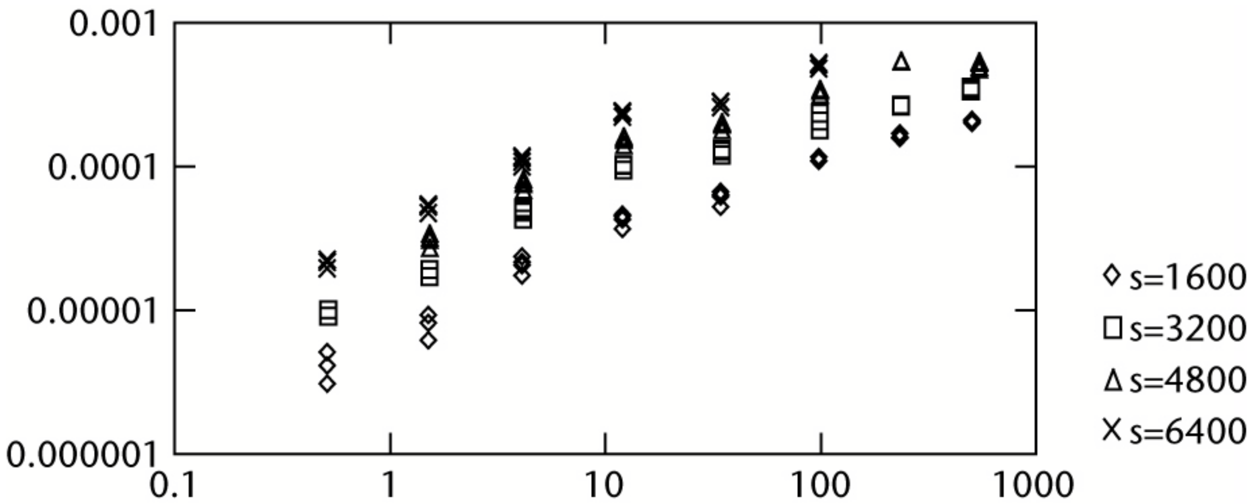

Figure 4: Relation between signal integral and particle volume.

Figure 5 shows the estimated particle volume from the model versus the known volumes. The results are shown with both arithmetic and logarithmic axes in order to clearly show the results for the smaller volumes. The y-scale of the logarithmic plot is divided into size class regions. With this model, the median error in particle volume estimation is ±13%, with a maximum error of 89%. While there is substantial error, estimates generally fall within the appropriate size class region.

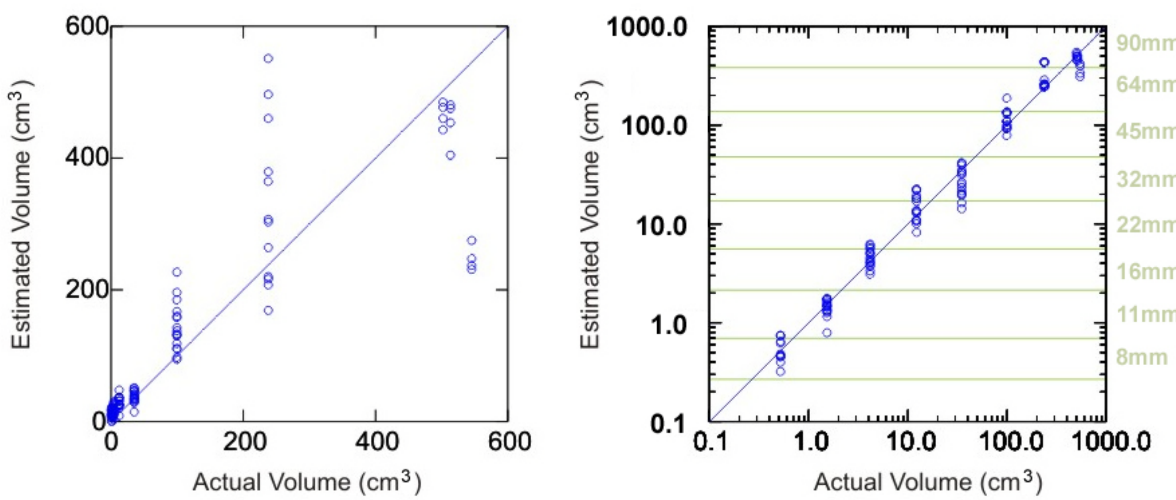

Figure 5: Estimate of particle volume from the integral empirical model versus actual volume. The horizontal lines on the plot divide the y-axis into size classes. Variability about the 1:1 line is generally within the correct size class.

Conclusions

Results from the empirical model indicate that it is possible to relate the signals recorded from the BMD sensor to particle size. However, the empirical model assumes the trajectory of the particle is directly across the center of the sensor, and that the particle is in contact with the bed (i.e., sensor-to-particle distance is fixed). Since this system is intended to measure the movement of gravel sized particles, assuming that particles move in contact with the bed is justifiable (fixing sensor-to-particle distance as long as sediment is not allowed to accumulate on top of the sensor). However, particles will not always travel directly over the center of the sensor. With the current sensor design, there is large variability in the magnetic field strength at the edge of the sensor compared with the center of the sensor. This causes large differences in the signal response to the same particle passing over the edge or the center of the sensor.

The benefits of the BMD system (automated, passive monitoring of bed load) continue to make this an attractive method for measuring bed load transport. Research is ongoing to further develop the BMD system, including alternative sensor design to produce more uniform magnetic fields in order to reduce particle trajectory effects, and use of more advanced signal processing methods for data analysis..

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